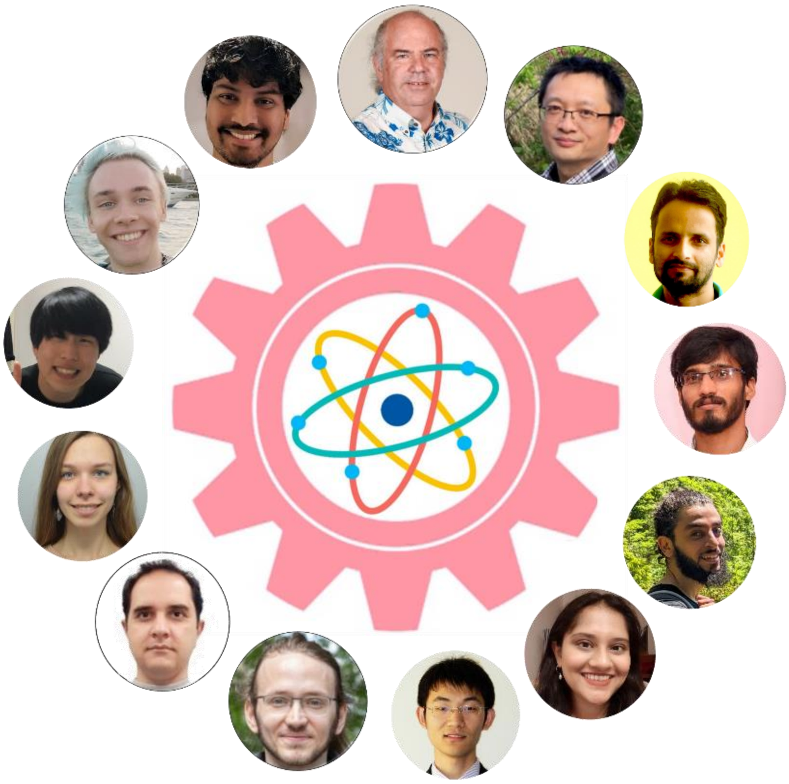
Quantum Machines Annual Report FY2023



Abstract

The Quantum Machines Unit undertakes research focused on hybrid quantum systems – which brings together two or more quantum systems to function together to perform some useful action, e.g. developing ultra-precise sensors, exploring fundamental issues in quantum science, or quantum information processing. We are interested in questions like: can we build table-top setups to explore the interaction of gravity with the quantum world? Can we build table-top setups to search for gravitational waves? Can we generate a Schrodinger cat in a massive particle – splitting the particle to exist in two places at once? Towards answering these questions the Quantum Machines Unit focuses on two primary tools: cavity optomechanics and magnetically levitated quantum systems. Cavity optomechanics involves optical cavities which involve optical elements which can move, e.g. a moving mirror. Optomechanics research has rapidly evolved into a large and dynamic research topic, developing new types of sensors and the cooling of small particles to their motional ground state. Diamagnetic levitation permits one to levitate quite large particles where one seeks to control the dynamics of individual and multiple particles using a variety of methods including real-time feedback control using optical and electromagnetic forces. Diamagnetic levitation requires no active power and is expected to exhibit very low levels of motional noise. The Quantum Machines Unit combines theory with experiment to develop these tools towards addressing the broader questions above.

1. Group Members

As of Jun 30, 2024

- Prof. Jason Twamley, Professor
- Dr. Jinjin Du, Staff Scientist
- Dr. Anil Kumar, Staff Scientist
- Dr. Kani Mohamed, Staff Scientist
- Dr. Mohamed Hatifi, Postdoctoral Scholar
- Dr. Krishna Jadeja, Postdoctoral Scholar
- Dr. Shilu Tian, Postdoctoral Scholar
- Dr. Steven Sagona-Stophel, Postdoctoral Scholar
- Dr. Mojtaba Moshkani, Postdoctoral Scholar
- Tatiana Iakovleva, Graduate Student
- Daehee Kim, Graduate Student
- Alexander Henry Hodges, Graduate Student
- Anshuman Nayak, Graduate Student
- Shuma Oya, Graduate Student (rotation Term 1 AY2023)
- Savelii Dudoladov, Graduate Student (rotation Term 1 AY2023)
- Miwa Matsui, Research Administrator

Alumni

- Dr. Fernando Quijandria, Staff Scientist (Nov 2021-Apr 2024)
- Dr. Ruvi Lecamwasam, Postdoctoral Scholar (Jun 2021-Jun 2023)
- Dr. Yanan Liu, Postdoctoral Scholar (Mar 2021-May 2022)
- Dr. Priscila Romagnoli, Postdoctoral Scholar (Sep 2020-Jul 2022)
- Dr. Sangkha Borah, Postdoctoral Scholar (Aug 2020-Nov 2022)
- Dr. Bijita Sarma, Postdoctoral Scholar (Jan 2021-Nov 2022)
- Dr. Isha Sanskriti, Postdoctoral Scholar (Jan 2021-Jan 2022)
- Breno Calderoni, Research Intern (Nov 2023-Mar 2024)
- Cristina Sastre, Research Intern (Oct 2023-Mar 2024)
- Sana Khalil, Research Intern (Jul 2023-Sep 2023)
- Camila Patricia Cusicanqui Padilla, Research Intern (Apr 2023-Jun 2023)
- Deepthi Parandhaman Gowrappan, Research Intern (Feb 2023-May 2023)
- Christopher Alan Arden Wise, Research Intern (Jan-Apr 2023)
- Andreas Raikos, Research Intern (Nov 2022-Mar 2023)
- Karina Yadav, Research Intern (Sep 2022-Feb 2023)
- Samuel Begumya, Graduate Student (rotation Term 3 AY2022)
- Zhenghan Yuan, Graduate Student (rotation Term 3 AY2022)
- Sougato Chowdhury Graduate Student (rotation Term 2 AY2022)
- Anshuman Nayak Graduate Student (rotation Term 2 AY2022)
- Alexander Hodges Graduate Student (rotation Term 1 AY2022)
- Amal Jose, Graduate Student (rotation Term 3 AY2021)
- Raul Alejandro Hidalgo Sacoto, Graduate Student (rotation Term 3 AY2021)
- Dr. Glemarie Hermosa,Visiting Researcher (Dec 2022-Mar 2023)
- Prof. Rong Zhang, Research Fellow (Nov 2022-Oct 2023)

- Prof. Jingbo Wang, Visiting JSPS Professorial Fellow (Jun-Jul 2022)

2. Collaborations

Type of collaboration:

- Joint research
    - Researchers:
    - Prof Thomas Busch, Okinawa Institute for Science and Technology, Okinawa, Japan
    - Prof James Downes, Prof Dave Spence, Prof Gavin Brennen, Dr Cyril Laplane, Macquarie University, Sydney, Australia
    - Dr Luke Trainor, University of Otago, New Zealand
    - Dr Maria Fuwa, AIST – National Institute for Industrial Science and Technology, Tokyo, Japan
    - Prof Gerard J. Milburn, University of Queensland, Queensland, Australia
    - Profs Kazuyuki Takeda and Y. Minowa, Kyoto University, Japan
    - Prof Jingbo Wang, Dr Maxim Goryachev, University of Western Australia, Perth, Australia
    - Profs Mutsuko Hatano and Kentaro Somiya, Tokyo Institute of Technology, Japan
    - Dr Motoki Asano, NTT Corporation, Japan
    - Prof Fedor Jelezko, University of Ulm, Germany
    - Prof Rong Zhang, University of Post and Telecommunications, Nanjing, China
    - Prof Sougato Bose, University College London, UK
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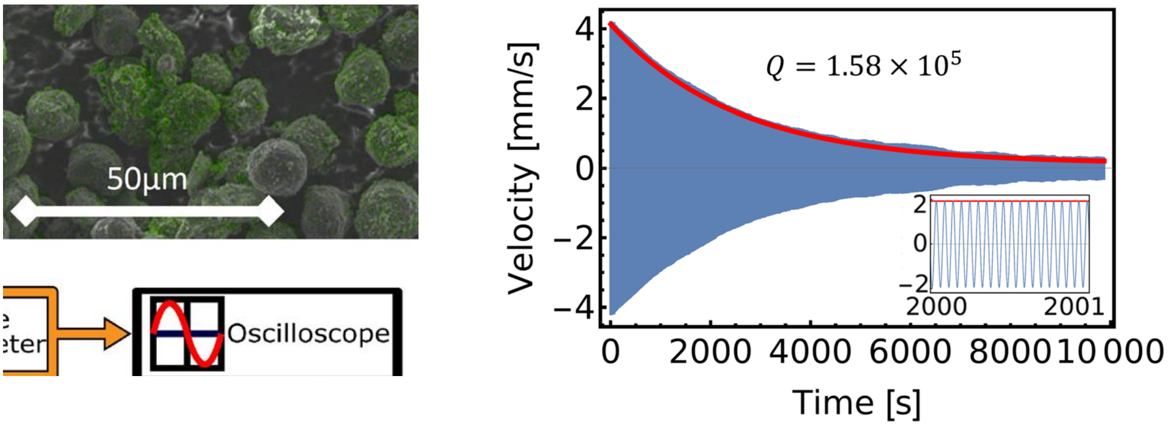
3. Activities and Findings

3.1 Fabrication of new material for high quality levitators and cooling its motion

The levitation of an object in vacuum is a good way to isolate the object’s motion from environmental noise. Such extreme isolation is necessary to cool the motion of the object towards the quantum regime. Most methods to levitate an object in vacuum only work for very small objects, either on the nanoscale or on the micro scale. Magnetic levitation can levitate very large objects: it can even levitate entire trains. In the Quantum Machines Lab we use magnetic levitation of diamagnetic objects. An object which is diamagnetic is repelled by all magnetic fields and one can levitate a diamagnetic material above very strong magnets using no active power. Since this type of levitation requires no active power we expect it to experience low noise and this will help us engineered the motion of the object towards the quantum regime. Previously we published experimental work to reduce the Eddy current damping in diamagnetic graphite slabs which we magnetically levitate above four permanent magnets. To do that we cut many tiny slots into the graphite slabs which then interrupted the Eddy currents from flowing and reduced the Eddy damping of the levitated slabs. This permitted us to increase the motional quality factor to a few 1000. However, our goal is to increase this quality factor even higher. In more recent work we fabricated an entirely new material which was highly diamagnetic but also electrically insulating so that it suffered very little Eddy damping. By forming small plates of this new material, we demonstrated that it could levitate above the magnets and when we evacuated the air from the chamber surrounding the levitated plate, we measured the quality factor to be over 100,000. This means that once set in motion, it takes several hours to stop. With this high-quality motional oscillator, we were able to perform feedback cooling. Feedback cooling is where we monitor the motion of the levitated plate in real time and apply forces in real time to slow it down and stop it moving. We were able to decrease its motional temperature by a factor of 1000. If we assume its initial motional temperature is at room temperature, we cool it to ~300mK. At such a motional temperature the levitated plate could act as a very precise accelerometer – beating almost every known accelerometer sensor. This work was published in Applied Physics Letters [Appl. Phys. Lett. 124, 124002 (2024)].



Caption: [Left] Experimental scanning electron microscope image of the new material which is both diamagnetic and electrically insulating. The false green color indicates the coating of an electrically insulating materials over small graphite beads. [Right] Experimental ring-down curve when a small plate made from the new material is levitated above magnets and given a small kick in high vacuum. It oscillates for several hours before stopping.

3.2 Feedback with gain to investigate precision clocks

Clocks and timing are central to our technology today. Atomic clocks provide very accurate timing but they are expensive and difficult to use. What types of precise clocks are used more commonly? In electronics one can build a clock – or oscillator – by using a differential amplifier and feeding the output back to the input with some gain. This type of feedback oscillator, when implemented, using optoelectronics, can produce some of the most precise "consumer" oscillators with incredible phase stability. We wanted to explore if the quantum version of such a feedback oscillator could also produce very accurate and stable oscillators. We looked at this theoretically and numerically – and discovered that the topic of feedback has been extensively studied in quantum systems only if the feedback is instantaneous. If there is some delay then the theoretical treatment for this feedback explodes in difficulty. Undaunted we examined the case of a quantum linear system subject to delayed feedback with gain and found – as we had hoped – that the system exhibits extremely precise phase stability. This is despite the individual components in the system are lossy. It is not a free lunch however, as the energy of this system grows in time. To limit this growth we instead looked at a nonlinear quantum system with feedback and gain and in that case the energy remains bounded but the oscillator loses phase coherence. This work was published in New Journal of Physics [New J. Phys. 25, 123032 (2023)]

3.3 Modelling photothermal effects in high-powered optomechanics

Optomechanics is the science which studies the interaction of light with an object that can move due to the force of the light on that object. Some of the most precise sensors in the world are based on optomechanical systems. By trapping light between two extremely good mirrors can lead to enormous optical powers circulating inside the optical cavity. Researchers have previously proposed to use such enormous powers to levitate one of the end mirrors of such a cavity – if the mirror is light enough. However, there are many other effects which can arise in such a situation which can compete and perhaps be stronger than the traditional optomechanical force. No mirror is 100% reflective and the small fraction of light power absorbed by the mirror can cause significant local heating- deforming the mirror. This is known as the photothermal effect in cavity optomechanics and it has proven difficult to find a good model for this phenomena as it can depend on many factors. In this work, in collaboration with researchers in Australia and Singapore, we build a refined theoretical model for this and other effects that arise in high-powered optomechanics and compare it with experimental observations. This work was published in New Journal of Physics [New J. Phys. 25 123051 (2023)]

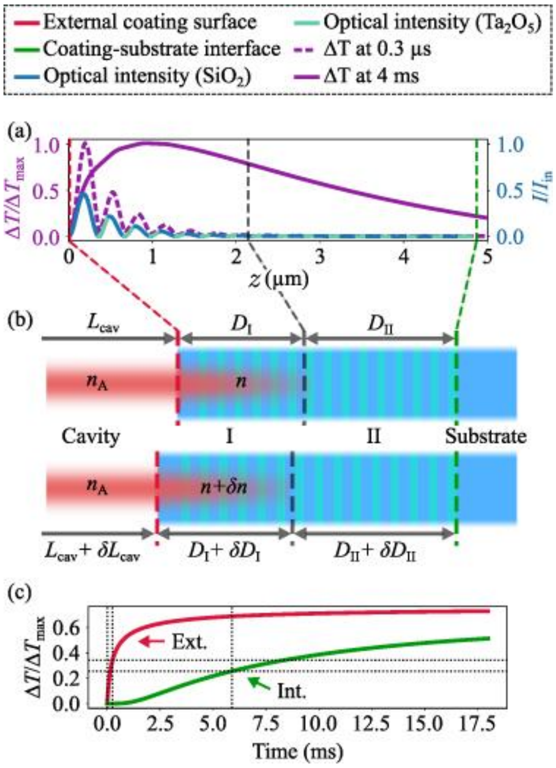


Fig caption: model of the photothermal expansion and thermo-optic effect in the Bragg coating of one end mirror in a high—powered optomechanical system [From NJP25, 123051 (2023)]

3.4 Quantum process tomography using learning of Krauss operators

Noise is one of the main obstacles in quantum computing. Determining the types of noise present in a quantum computer allows one to design specific quantum error correction codes to best fight the noise. Noise makes a good quantum system bad and the process of evolving from a good to bad quantum state is known in the community as a Quantum Process. It is possible to perform many many measurements to map out this process and the procedure to do this is known as Quantum Process Tomography (QPT). There are a number of protocols which have been invented to perform QPT and each has pros and cons. Some require enormous numbers of measurements as the quantum system scales up while others can use small numbers of measurements but yield a poor approximation to the true quantum process. Some return quantum processes which are not even possible via quantum mechanics and thus one has to find the closest viable quantum process. In this work, a collaboration with Chalmers University in Sweden, we look at measurements to learn things about the Krauss operators – which are the mathematical objects that generate the process. We discover a protocol to uncover a level of information about the Krauss operators so that one can get a reasonable understanding of the quantum process that is really going on in the device. The protocol scales well with increasing number of qubits and can operate with just a few random measurements. This work was published in Physical Review Letters [Phys. Rev. Lett. 130, 150402 (2023)].

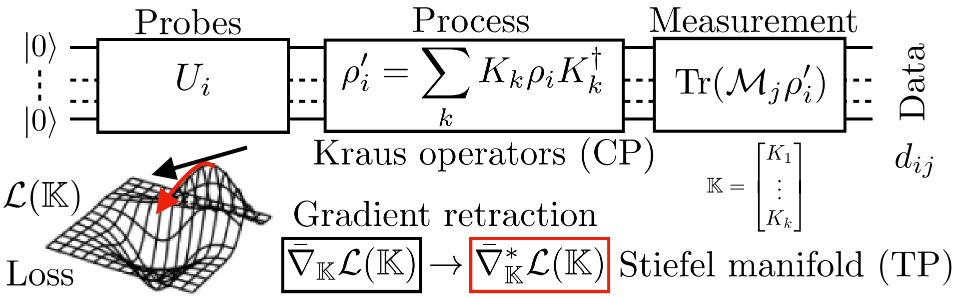


Fig caption: Schematic of the protocol to learn the quantum process of an open quantum system by learning the Krauss operators generating the process [from PRL 130, 150402 (2023)]

4. Publications

4.1 Journals

Tian, S., Jadeja, K., Kim, D., Hodges, A., Hermosa, G.
C., Cusicanqui, C., Lecamwasam, R., Downes, J. E., Twamley, J.
Feedback cooling of an insulating high-Q diamagnetically levitated plate*,
Appl. Phys. Lett. 124, 124002 (2024)

Gu, CY., Qin, JY., Guccione, G., MA, JY., Lecamwasam, R., Lam, PK.
Modeling photothermal effects in high power optical resonators used for coherent levitation*,
New J. Phys. 25 123051 (2023)

Liu, Y., Munro, WJ., Twamley, J.
A quantum ticking self-oscillator using delayed feedback*
New J. Phys. 25, 123032 (2023)

Lu, Y., Kundra, M., Hillmann, T., Yang, JY., Li, HX., Quijandria, F., Delsing, P.
Resolving Fock states near the Kerr-free point of a superconducting resonator*
NJP Quantum Info 9, 114 (2023)

Ahmed, S., Quijandria, F., Kockum, AF.
Gradient-Descent Quantum Process Tomography by Learning Kraus Operators*
Phys. Rev. Lett. 130, 150402 (2023)

Jolin, SW., Andersson, G., Hernandez, JCR., Strandberg, I., Quikandria, F.,
Aumentado, J., Borgani, R., Tholen, MO., Haviland, DB.
Multipartite Entanglement in a Microwave Frequency Comb*
Phys. Rev. Lett. 130, 120601 (2023)

Romagnoli, P., Lecamwasam, R., Tian, S., Downes, JE., Twamley, J.
Controlling the motional quality factor of a diamagnetically levitated graphite plate*
Appl. Phys. Lett. 122, 094102 (2023)

Chen, X., Lu, XJ., Liu, Y. Kuang, S.
Comparison of differential evolution, particle swarm optimization, quantum-behaved particle swarm optimization, and quantum evolutionary algorithm for preparation of quantum states
Chinese Phys B, 32 020202 (2023)

4.2 Books and other one-time publications

Nothing to report

4.3 Oral and Poster Presentations

Invited Talk: A. Kani: “Magnonic Einstein–de Haas Effect,” University of Duisburg-Essen, Germany, February 7, 2023

Oral: S Tian: "Feedback cooling of cm sized levitated oscillators,” Feedback in Quantum Machines 2023, OIST, November 27-December 1, 2023.

Oral: S Tian: "Feedback cooling of magnetically-levitated cm-size resonators,” 1st International Workshop on Quantum Information Engineering (QIE2023), OIST, 2023.

Poster: A. Kani: "Rotational Cavity Magnomechanics,” Quantum Innovation 2023, Tokyo, November 15-17, 2023.

Poster: Anil Kumar Chauhan: "Tuneable Gaussian entanglement in levitated nanoparticles,” Quantum Innovation 2023, Tokyo, November 15-17, 2023.

Poster: S Tian: "Massive quantum superpositions using superconducting magneto-mechanics,” Quantum Innovation 2023, Tokyo, November 15-17, 2023.

Poster: S Tian: "Feedback cooling of magnetically-levitated cm-size resonators,” Quantum Innovation 2023, Tokyo, November 15-17, 2023.

Poster: K. Jadeja: "Levitation of cm-sized platforms for quantum sensing and computation,” Southwest Quantum Information and Technology Workshop, New Mexico, USA, October 26-28, 2023.

Poster: S Tian: " Engineering Q factor of diamagnetically levitated graphite resonator,” Seminar "Exploiting Levitated Particles in the Quantum Regime", Germany, September, 2023.

Poster: T. Iakovleva: "Zeptometer displacement sensing using cavity opto-magneto-mechanics,” Quantum sensing and fundamental physics with levitated mechanical systems, Italy, July 31-August 3, 2023.

Poster: Kim, D: "A magnetically tunable lens – Converging Horizons," NTT x OIST Joint Workshop, OIST, February 8, 2024.

Poster: Kim, D: "Levitated optomechanics for quantum sensing and fundamental science – Converging Horizons," NTT x OIST Joint Workshop, OIST, February 8, 2024.

Poster: Kim, D: "Levitation of cm-sized platforms for quantum sensing and computation," Feedback in Quantum Machines 2023, OIST, November 27-December 1, 2023.

Poster: Kim, D: "Feedback cooling of magnetically-levitated cm-size resonators," Quantum Innovation 2023, Tokyo, November 15-17, 2023.

Poster: A. Hodges: "Levitated Graphite: From Room Temperature to 320mK," GRC Quantum systems in the mechanical regime, Ventura CA, March 3-4, 2024.

Poster: A. Hodges: "Cooling & Control of Macroscopic, Diamagnetically Levitated Resonators," Optomechanics and nanophononics, Les Houches School of Physics, France, April 17-28, 2023.

Poster: Nayak, A: "Ultrasensitive Solid-State Gyroscope Based on Nuclear Spins in Diamond," Quantum Innovation 2023, Tokyo, November 15-17, 2023.

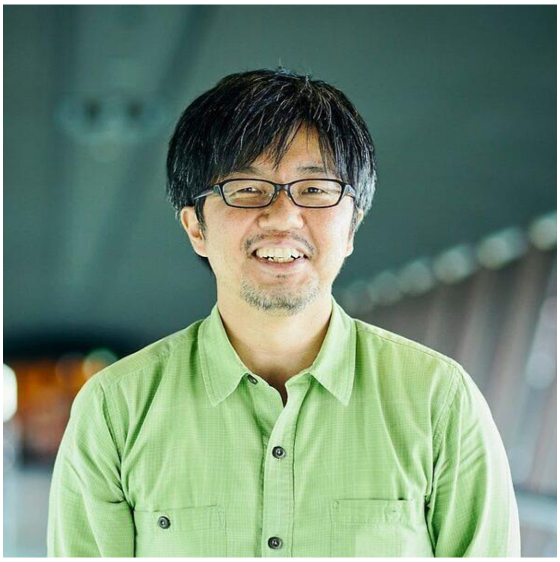
5. Intellectual Property Rights and Other Specific Achievements

Provisional Patent filed in Japan: Frequency combs in the microwave range by A. Kani and M. Hatifi, and J.Twamley 2023/11/28

6. Meetings and Events

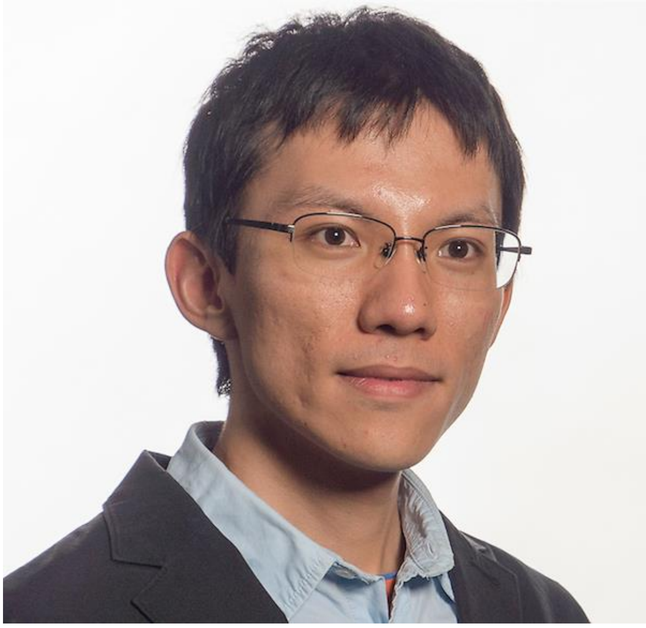
6.1 Seminars

1. Prof Hiroki Takahashi, PI of the EQIP Unit, OIST
Title: Optical fiber Fabry-Perot cavities: Production and applications
Date: April 13, 2023
Time: 10:00
Seminar details:
https://groups.oist.jp/qmech/event/seminar-optical-fiber-fabry-perot-cavities-production-and-applications



2. Prof. Prof Tim Taminiau, QuTech
Title: Quantum networks based on diamond spin qubits
Date: April 20, 2023
Time: 16:00
Seminar details:
https://groups.oist.jp/qmech/event/quantum-networks-based-diamond-spin-qubits-prof-t-taminiau-qutech

3. Dr. Akio Kawasaki, National Institute of Advanced Industrial Science and Technology
Title: Control and characterization of optically-levitated microspheres for applications to fundamental physics
Date: May 18, 2023
Time: 16:00
Seminar details:
https://groups.oist.jp/qmech/event/control-and-characterization-optically-levitated-microspheres-applications-fundamental



4. Prof. Yaroslav M. Blanter, Delft University of Technology
Title: Cavity Magnonics
Date: May 25, 2023
Time: 16:00
Seminar details:
https://groups.oist.jp/qmech/event/seminar-cavity-magnonics

5. Dr. Marko Toroš, University of Glasgow
Title: Generation of entanglement from mechanical rotations
Date: June 15, 2023
Time: 16:00
Seminar details:
https://groups.oist.jp/qmech/event/generation-entanglement-mechanical-rotations

6. Dr. Cyril Laplane, Macquarie University
Title: Levitodynamics of optically active nanocrystals
Date: June 22, 2023
Time: 16:00
Seminar details:
https://groups.oist.jp/qmech/event/levitodynamics-optically-active-nanocrystals

7. Ms.Trisha Madhavan, Harvard University
Title: Toward On-Chip Spin Magnetomechanics with Levitated Systems
Date: December 14, 2023
Time: 09:00
Seminar details:
https://groups.oist.jp/qmech/event/toward-chip-spin-magnetomechanics-levitated-systems

8. Prof Mutsuko Hatano, Tokyo Institute of Technology
Title: Potential of Diamond Quantum Sensors
Date: March 12, 2024
Time: 16:00
Seminar details:
https://groups.oist.jp/qmech/event/potential-diamond-quantum-sensors

9. Dr. Josephine Dias, OIST
Title: Strategies for charging open quantum batteries
Date: April 11, 2024
Time: 14:00
Seminar details:
https://groups.oist.jp/qmech/event/strategies-charging-open-quantum-batteries

10. Dr. Jack Clarke, Imperial College London
Title: Cavity Quantum Optomechanical Nonlinearities: from Position Measurement Beyond the Linearized Regime to Deterministic Mechanical Nonclassicality
Date: April 18, 2024
Time: 17:00
Seminar details:
https://groups.oist.jp/qmech/event/seminar-zoom-cavity-quantum-optomechanical-nonlinearities-position-measurement-beyond

7. Other

7.1 Events

- OIST Workshop "Feedback control of Quantum Machines" Nov 27-Dec 1 2023 [Link]

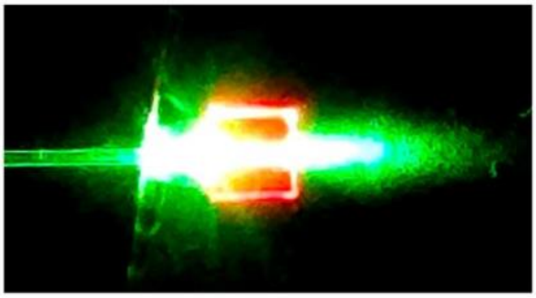
- OIST Science Festival 2023 Nov 11 [Link]:

  We organized the OIST Centre for Quantum Technologies to host a table for the public and school children to
  highlight the wonders of the quantum world. This extended exhibit was entitled:

  EXPERIENCE THE AMAZING POWER OF THE QUANTUM WORLD

  At this one day event we had ~1000 public visit and we had working demonstrations of:

  - Electrodynamic trapping of dust particles
  - Fluorescence of Diamond containing Nitrogen Vacancy defects
  - Diamagnetic Levitation



- “Come chat with Serge” with Professor Serge Haroche, Nobel Prize – May 19th 2023 [Link]

- **Media Releases and Coverage of the QMU Research**
    - March 2024: Innovative magnetic levitation: New material offers potential for unlocking gravity-free technology [Link]
    - March 2024: Coverage of Media Release “going viral” in multiple media outlets [Link]