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# Plasma Division

Development of High Power Microwave Source

Project ID: ARY1 Primary Supervisor: Alan Young **Division:** Plasma **Email:** a.r.young@strath.ac.uk

**Secondary Supervisor(s):** Kevin Ronald **Project Background:** Microwaves are used extensively in modern life from the ubiquidous oven to wifi, mobile phones and satelite communications. There is a significant need for more powerful sources of microwaves, particularly at high frequencies for use in Radar and communications. This project will study the feasibility of a possible source for the heating of fusion plasmas through the use of computer simulations.

Aim: To use simulation software to develop models of high power microwave sources.

**Tasks:** Review the theory of 'fast wave' high power microwave sources. Gain a working knowledge of CST studio. Using CST studio study the performance of fast wave devices.

#### **Key References:**

[1] Phelps, A.D.R. & Cross, A.W. & He, W. & Cooke, Simon. (1998). CARM Experiments with Cold and Thermionic Cathodes. 429-433.

[2] G. G. Denisov, V. L. Bratman, A. D. R. Phelps, and S. V. Samsonov, "Gyro-TWT with a helical operating waveguide: New possibilities to enhance efficiency and frequency bandwidth," IEEE Trans. Plasma Sci., vol. 26, no. 3, pp. 508–518, Jun. 1998.

[3] G. Burt, S. V. Samsonov, K. Ronald, G. G. Denisov, A. R. Young, V. L. Bratman, A. D. R. Phelps, A. W. Cross, I. V. Konoplev, W. He, J. Thomson, and C. G. Whyte, "Dispersion of helically corrugated waveguides: Analytical, numerical, and experimental study," Phys. Rev. E, vol. 70, no. 4, pp. 046402-1–046402-8, 2004.

Project Composition:Theory: 30%Computation: 70%Experimentation: 0%

**Recommended Background or Pre-Requisites:** Student will need general computer skills and be prepared to learn to use the simulation tool CST studio.

Additional Safety Training required: No special training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student can take this project

### Novel THz sources based on oversized periodic lattice interaction structures

#### Project ID: AMc1

**Division:** Plasma **Email:** amy.maclachlan@strath.ac.uk

Primary Supervisor: Amy MacLachlan Secondary Supervisor(s): Kevin Ronald

**Project Background:** The generation of powerful electromagnetic radiation at terahertz (0.1 to 10THz) frequencies is a long-standing physics challenge. Research into THz radiation sources has been stimulated by applications in fusion science, biochemical spectroscopy, non-destructive testing, radar and remote sensing. In traditional radiation sources based on a backward-wave interaction, the transverse dimension of the interaction region is comparable to the free-space radiation wavelength ( $\lambda$ ), ensuring phase and spectral coherence of the output radiation but restricting the output power (P~ [1/f] ^2) at high frequencies. The interaction volume can be increased, while avoiding the excitation of parasitic modes, through the use of a two-dimensional surface lattice interaction structure. The 2D corrugations mediate the formation of a cavity eigenmode, composed of coupled volume and surface waves. The excitation of this eigenmode provides the conditions required for stable operation.

Coherent radiation is generated by the Cherenkov interaction between the cavity eigenmode and a thin annular electron beam. Cherenkov radiation occurs when charged particles propagate in, or near, a medium capable of supporting slow (in respect to the speed of light) electromagnetic waves with an axial phase velocity less than the drift velocity of the electrons. Coupling occurs between the space charge wave (electron bunches) of the electron beam and the electric field components of the wave orientated along the direction of the particle drift. The space charge wave originates from modulation of the electron energy by the electromagnetic field, leading to the formation of spatial bunches in the electron stream.

This project explores the physics of the complicated coupling between electromagnetic fields and electron beams in Cherenkov sources based on periodic surface structures with diameters several times greater than the radiation wavelength for important applications.

**Aim:** Explore the physics of the electromagnetic and electrodynamic coupling in novel Cherenkov sources operating in the steady-state

**Tasks:** Undertake a literature review of the electromagnetic theory, electron beam-wave interaction processes, 1D and 2D periodic structures. Understand key theoretical and numerical methods. Adapt an existing computer model and perform calculations to investigate the effects of varying the lattice and electron beam parameters on the electromagnetic and electrodynamic coupling processes.

#### **Key References:**

MacLachlan, A. J., Robertson, C. W., Konoplev, I. V. et al 2019 Phys. Rev. Appl. 11, 034034
 MacLachlan, A. J., Robertson, C. W., Cross, A. W. et al 2022 IEEE Trans. Electron Dev. 69, 11
 MacLachlan, A. J., Robertson, C. W., Cross, A. W. et al 2023 IEEE Trans. Electron Dev. 70, 6

Project Composition: Theory: 40% Computation: 60% Experimentation: 0%

**Recommended Background or Pre-Requisites:** Strong background in EM theory, vectors and vector calculus and mechanics/dynamics. It is recommended that students should be taking PH452 and (in due course) PH560.

Additional Safety Training required: Standard departmental safety induction Suitable for: MPhys, Bsc, BSc Maths and Physics Notes:

### Generation of THz super pulses

Project ID: AMc2

**Division:** Plasma **Email:** amy.maclachlan@strath.ac.uk

Primary Supervisor: Amy MacLachlan Secondary Supervisor(s): Kevin Ronald

**Project Background:** The ability to generate terahertz "super pulses" by driving Cherenkov masers into the highly nonlinear superradiative regime is an exciting topic in physics. The term "superradiance" was first used by Dicke in 1954 to describe coherent photon emission from a gas. A defining feature of superradiance is that the signal strength is directly proportional to the number of oscillators squared. Similar observations, beyond the strict definition of Dicke superradiance, have been made in atomic physics, quantum mechanics, astrophysics and free electron physics to describe radiation enhancement processes with similar scaling.

This project explores Cherenkov superradiance arising from the transient slippage interaction between a relativistic electron beam and an electromagnetic wave.

Cherenkov radiation occurs when electrons propagate in, or near, a medium capable of supporting slow (in respect to the speed of light) electromagnetic waves with an axial phase velocity less than the drift velocity of the electrons. For superradiance, the group speed of the electromagnetic wave relative to the drift velocity of the electrons must be in the correct range. In this process, the wave rapidly soaks energy from the electrons, or vice versa, compressing the energy into a an exceptionally powerful, short duration "super pulse". The aim of this project is to establish optimum slippage conditions to drive superradiance in Cherenkov masers based on periodic surface lattice interaction structures.

**Aim:** Explore the optimum parameters and slippage conditions for superradiance in Cherenkov sources based on periodic surface lattice interaction structures

**Tasks:** Undertake a literature review of the electromagnetic theory, electron beam-wave interaction processes, periodic structures and superradiance. Understand key theoretical and numerical methods. Adapt an existing computer model and perform calculations to investigate the conditions for superradiant emission in the THz spectral range.

#### **Key References:**

[1] MacLachlan, A. J., Robertson, C. W., Cross, A. W. et al 2022 IEEE Trans. Electron Dev. 69, 11

[2] Ginzburg N S, Novozhilova Yu V, Zotova I V et al. 1998 Tech. Phys. Lett. E 24 9

[3] Ginzburg, N. S., ZaSlavskii, V. Yu., Malkin, A. M. et al. 2017 Tech. Phys. Lett. 43, 8

Project Composition:	Theory: 40%	Computation: 60%	<b>Experimentation:</b> 0%
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**Recommended Background or Pre-Requisites:** Strong background in EM theory, vectors and vector calculus and mechanics/dynamics. It is recommend that students should be taking PH452 and (in due course) PH560.

Additional Safety Training required: Standard departmental safety induction Suitable for: MPhys, Bsc, BSc Maths and Physics Notes:

### Design and optimisation of a plasma-flare based electron injector for metamaterial studies

#### Project ID: DS1

Division: Plasma Email: david.c.speirs@strath.ac.uk

Primary Supervisor: David Speirs Secondary Supervisor(s): Kevin Ronald

**Project Background:** A metamaterial is a type of synthetic, structured material that exhibits unusual electromagnetic, acoustic or mechanical properties that can prove useful in a variety of applications. In the current context, the metamaterials of interest have unusual electromagnetic dispersive properties that make them highly suited to the tuneable and efficient generation of microwaves. To evaluate such materials for microwave generation, a suitable high-current accelerator is required to provide a rectilinear electron beam with low velocity spread at energies of up to 100keV. The objective of this project is to design and optimise a plasma-flare based electron injector to meet the requirements of experiments using prototype metamaterial resonators. The project will require a combination of analytical / theoretical calulcations to compute the initial geometrical and electrical parameters of the electron injector, followed by advanced fully-electromagnetic particle-in-cell (PiC) code simulations to further optimise and evaluate the performance of the high current accelerator. **Aim:** The objective is to design and optimise a plasma-flare cathode based electron injector to generate a suitable, magnetically constrained electron beam for the study of resonant metamaterial structures that can generate tuneable, microwave radiation in the X-band.

**Tasks:** 1. Literature review on high-current accelerator physics and plasma-flare electron emission. 2. Analytical calculation of the initial electrical and geometrical parameters of the electron injector. 3. Construction of a fully-electromagnetic, 3D PiC (Particle-in-Cell) code model of the electron accelerator, suitably parameterised to evaluate and refine the design specifications against the requirements for metamaterial resonator experiments. **Key References:** 

[1] R. G. Carter, Microwave and RF Vacuum Electronic Power Sources, pp. 317-351 (2018) https://doi.org/10.1017/9780511979231.009

[2] D. L. Shmelev and S. A. Barengolts, IEEE Transactions on Plasma Science, 41, 1964-1968 (2013) https://doi.org/10.1109/TPS.2013.2244921

[3] C. K. Birdsall and A. B. Langdon, Plasma Physics Via Computer Simulation,

Taylor & Francis Ltd (October 2004) https://doi.org/10.1201/9781315275048

Project Composition:Theory: 30%Computation: 70%Experimentation: 0%

**Recommended Background or Pre-Requisites:** Some experience of programming in Python would be useful. An understanding of electromagnetic theory, particularly Maxwell's equations would be highly relevant to this project.

Additional Safety Training required:

**Suitable for:** Mphys, BSc, MSc Maths and Physics. **Notes:** One student can take this project.

### Charge cross-calibration of scintillating screens for imaging electron spectrometer

#### Project ID: GM1

#### **Division:** Plasma **Email:** grace.manahan@strath.ac.uk

Primary Supervisor: Grace Manahan Secondary Supervisor(s): Mark Wiggins

**Project Background:** Plasma-based accelerators have the potential to be the next generation sources for light sources applications. Electron beams from these accelerators are typically characterised via their energy, charge and beam pointing stability. Diagnostics with scintillating screens such as lanex and YAG screens are mostly used to image these beam. In this project, the student will characterise and obtain a charge cross calibration of the lanex screens for an imaging electron spectrometer. This spectrometer has been commissioned and conssitently being used at the laser wakefield beamline of SCAPA. The student will also have the opportunity to participate in one of the experimental campaign here are SCAPA.

Aim: To characterise the imaging system of an electron spectrometer used at the LWFA beamline of SCAPA. Tasks: Tasks: (1). Literature review of LWFA focusing on the diagnostics used for electron beam (electron spectrometer, lanex screen, imaging plates); (2) Create a python code that will be able to calculate and analyse the charge of an electron beam via imaging plates (3) Create a python code to obtain a sensitivity response of the imaging plates (4) Create a python code that will obtain a cross calibration curve of the lanex screens. Key References:

[1] G Boutoux et al, Study of imaging plate detector sensitivity to 5-18 MeV electrons.

(https://doi.org/10.1063/1.4936141)

[2] G. Jackson Williams, Calibration and equivalency analysis of image plate scanners.

(https://doi.org/10.1063/1.4886390)

[3] N Rabhi, Calibration of imaging plates to electrons between 40-180 MeV.

(http://dx.doi.org/10.1063/1.4950860)

Project Composition:Theory: 30%Computation: 65%Experimentation: 5%

**Recommended Background or Pre-Requisites:** In depth understanding on the concepts of plasma and laser physics. Basic knowledge in python programming language, particularly in image processing is crucial.

Additional Safety Training required: laser safety training Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student only

### Drilling using high-power microwaves

Project ID: LZ1

**Division:** Plasma **Email:** liang.zhang@strath.ac.uk

Primary Supervisor: Liang Zhang Secondary Supervisor(s): Kevin Ronald

**Project Background:** Exploration of off-Earth deep space is exciting and full of challenges. Effective and reliable drilling technology is crucial for scientific research and future mining endeavors. Direct Energy Drilling technology offers high energy efficiency and the capability to drill deeper through hard rock. It also has the advantage of no moving parts and does not transfer any torque to the lander, making it suitable for low-gravity environments. Microwave drilling has been studied on concrete, ceramic, bones, and other dielectric materials. Its application in the terrestrial geothermal industry is also currently being explored. This project aims to conduct a feasibility study on adapting microwave drilling technology for space applications. The study will investigate factors that affect the performance of microwave drilling, including drive power level, operating frequency, and material properties. The formation of holes due to microwave heating will be studied using a numerical model that couples microwave transmission and thermal effects. Validation of material properties will be carried out using a vector network analyser.

Aim: Investigate the feasibility to use microwave energy as a directed-energy driller in space application Tasks: Review the physics of microwave transmission and thermal conduction processes. Understand the microwave drilling mechanism. Summarize the factors that affect microwave drilling and the relationships among these factors. Conduct multi-physics simulations involving microwave and thermal processes. Learn to use vector network analysis to measure microwave transmission and the properties of dielectric materials. Key References:

 E. Jerby et al., The Microwave Drill.Science, vol. 298,587-589(2002). DOI: 10.1126/science.1077062
 E. Jerby, Y. Nerovny, Y. Meir, O. Korin, R. Peleg and Y. Shamir, "A Silent Microwave Drill for Deep Holes in Concrete," in IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 1, pp. 522-529, Jan. 2018, doi: 10.1109/TMTT.2017.2729509.

[3] Woskov, P.P. (2018). Gyrotron Based Melting. In 78th Conference on Glass Problems, S.K. Sundaram (Ed.). https://doi.org/10.1002/9781119519713.ch20

Project Composition:Theory: 30%Computation: 55%Experimentation: 15%

**Recommended Background or Pre-Requisites:** Students should be comfortable with using Matlab, or Python for simple numerical calculations, also will need to learn a new simulation tool CST Microwave Studio.

Additional Safety Training required: No special training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student can take this project

### Lunar drilling using high-power microwaves

#### Project ID: LZ2

**Division:** Plasma Email: liang.zhang@strath.ac.uk

Primary Supervisor: Liang Zhang Secondary Supervisor(s): Kevin Ronald

Project Background: Exploration of off-Earth environments is exciting and full of challenges. Effective and reliable drilling technology is crucial for scientific research, lunar exploration and future resource extraction. Direct Energy Drilling technology potentially offers high energy efficiency and the capability to drill deeper through hard rock, such as that thought to exist on the moon. It also has the advantage of no moving parts and does not transfer any torque to the lander, making it suitable for low-gravity environments. Microwave drilling has been studied on concrete, ceramic, bones, and other dielectric materials. Its application in the terrestrial geothermal industry is also currently being explored. This project aims to conduct a feasibility study on adapting microwave drilling technology for space applications. The study will investigate factors that effect the performance of microwave drilling, including drive power level, operating frequency, and material properties. The formation of holes due to microwave heating will be studied using a numerical model that couples microwave transmission and thermal effects. Methods to validate material properties using vector network analysis will be considered.

Aim: Investigate the feasibility to use microwave energy as a direct-energy drill in space application Tasks: Review the physics of microwave transmission and thermal conduction processes. Understand the microwave drilling mechanism. Summarize the factors that affect microwave drilling and the relationships among these factors. Conduct multi-physics simulations involving microwave and thermal processes. Learn to use vector network analysis to measure microwave transmission and the properties of dielectric materials.

#### **Key References:**

[1] E. Jerby et al., The Microwave Drill.Science, vol. 298,587-589(2002). DOI: 10.1126/science.1077062 [2] E. Jerby, Y. Nerovny, Y. Meir, O. Korin, R. Peleg and Y. Shamir, "A Silent Microwave Drill for Deep Holes in Concrete," in IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 1, pp. 522-529, Jan. 2018, doi: 10.1109/TMTT.2017.2729509.

[3] Woskov, P.P. (2018). Gyrotron Based Melting. In 78th Conference on Glass Problems, S.K. Sundaram (Ed.). https://doi.org/10.1002/9781119519713.ch20

**Project Composition: Computation:** 55% **Theory:** 30% **Experimentation:** 15%

Recommended Background or Pre-Requisites: Students should be comfortable with using Matlab, or Python for simple numerical calculations, also will need to learn a new simulation tool CST Microwave Studio.

Additional Safety Training required: No special training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student can take this project

### Electron beams from a laser-plasma wakefield accelerator for applications

#### Project ID: MW1

#### Division: Plasma Email: mark.wiggins@strath.ac.uk

Primary Supervisor: Mark Wiggins Secondary Supervisor(s): Grace Manahan

**Project Background:** Laser-plasma wakefield accelerators (LWFAs) are very compact laser-driven accelerators that have the potential to replace conventional accelerators or radiation sources in a broad range of applications. Highly relativistic electron beams are generated in an LWFA when a high-intensity femtosecond duration laser pulse is focused into a gaseous or plasma target. These electrons can then be used to generate very bright bursts of X-rays or gamma-rays for applications such as radioisotope production or high-resolution X-ray imaging that are the subject of upcoming experimental runs within the SCAPA facility.

Aim: To characterise highly relativistic electron beams for application in the SCAPA facility.

**Tasks:** Thorough literature review of the background topic areas (laser-plasma accelerators and applications, relativistic electron beams, beamline diagnostics). The student will take part in SCAPA application experiments acquiring and analysing electron beam data. Comparison made with theory and simulation on the efficacy of electron beams for generating X-rays or gamma-rays for secondary targets.

#### **Key References:**

[1] S. M. Hooker, "Developments in laser-driven plasma accelerators", Nature Photonics 7, 775 (2013).

[2] L. Mou et al., "67Cu Production Capabilities: A Mini Review", Molecules 27, 1501 (2022).

[3] F. Albert, "Principles and applications of x-ray light sources driven by laser wakefield acceleration", Phys. Plasmas 30, 050902 (2023).

Project Composition:	Theory: 20%	Computation: 20%	Experimentation: 60%
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**Recommended Background or Pre-Requisites:** Good practical physics skills. Interest in high-power lasers, radiation and applications.

Additional Safety Training required: Laser and ionising radiation safety training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes: Suitable for one student only.

### Modelling laser propagation in dense expanding plasma for KHz laser systems

Project ID: MK1

**Division:** Plasma **Email:** m.king@strath.ac.uk

Primary Supervisor: Martin King Secondary Supervisor(s): Ross Gray, Paul McKenna

**Project Background:** The propagation of intense laser pulses with dense plasma is a critical area of research in high-energy density physics and inertial confinement fusion (ICF). By ionising and expanding ultrathin foil targets, the resultant plasma can become transparent to the laser light enabling focusing of the pulse and acceleration of particles. Being able to investigate and utilise this behaviour at high repetition rates is key to developing plasma optical devices. This project will model the laser-plasma interactions at intensities achievable on a kHz laser system available at Strathclyde and determine the feasability of using such systems as a plasma optical device and/or as a source of high energy particles.

**Aim:** Investigate focusing effects and particle acceleration from laser-plasma interactions in expanding plasma. **Tasks:** 1) Determine appropriate expansion parameters for expanding plasma for a kHz system

2) Design and perform simulations of intense laser plasma interaction

3) Optimise focusing behaviour and/or particle acceleration

### **Key References:**

[1] Frazer, T.F. et al. "Enhanced laser intensity and ion acceleration due to self-focusing in relativistically transparent ultrathin targets" Physical Review Research, 2, 042015(R), 2020

[2] Daido, Hiroyuki, Mamiko Nishiuchi, and Alexander S. Pirozhkov. "Review of laser-driven ion sources and their applications." Reports on progress in physics 75.5 (2012): 056401.

[3]

Project Composition:Theory: 20%Computation: 80%Experimentation: 0%

**Recommended Background or Pre-Requisites:** Some background or experience with data analysis in python would be beneficial along with a keen interest in computational physics

Additional Safety Training required: Normal office/computer working Suitable for: BSc, Mphys Notes: One student can take this project.

### Developing an application for proton energy spectrum retrieval from a film-based diagnostic

Project ID: RW1 Primary Supervisor: Robbie Wilson Division: Plasma Email: robbie.wilson@strath.ac.uk

Secondary Supervisor(s): Ross Gray, Paul McKenna

**Project Background:** The interaction of an intense laser pulse (>10^18 W/cm2) with a solid density foil results in the acceleration of a large number (>10^8) of protons, up to 10's MeV energies, through various acceleration mechanisms. Characterisation of the energy spectrum of such experimentally is a fundamental measurement to gain insight into the laser-solid interaction and the generated source. A common method achieve this is to employ a stack of dosimetry film (radiochromic film, referred to as RCF) in the accelerated beam to image the protons at discrete energies. The resultant change in optical density of the film is then used to calculate the number of incident protons. To-date within our research group we have employed a MATALB code for the extraction of data from digitised film images, however with the wide adoption of Python within the field it is advantageous and timely to develop a new extraction process employing this coding language. This project will make an important contribution to the development of the laser-driven proton source being developed within the SCAPA facility at the university and the application-based investigations employing the source, such as radiobiology experiments for future cancer therapies and radiation damage testing of electrical components. **Aim:** To develop a python-based code to extract proton energy spectra from a film-based diagnostic employed in laser-driven proton acceleration studies.

Tasks: 1) Develop a basic python code to extract proton numbers for radiochromic film images

2) Compare code results to a previous version of the extraction software, historical measurements and models of laser-driven proton acceleration

3) Extent the usability of the developed code, with the addition of a GUI interface and methods to exact addition measurements from the films, such a proton beam divergence

#### **Key References:**

[1] F. Nurnberg et al., "Radiochromic film imaging spectroscopy of laser-accelerated proton beams," Review of Scientific Instruments, 80, 033301 (2009)

[2] M. Schollmeier et al. "Improved spectral data unfolding for radiochromic film imaging spectroscopy of laseraccelerated proton beams," Review of Scientific Instruments, 85, 043305 (2014)

[3] Daido, Hiroyuki, Mamiko Nishiuchi, and Alexander S. Pirozhkov. "Review of laser-driven ion sources and their applications." Reports on progress in physics 75.5, 056401 (2012)

Project Composition:Theory: 20%Computation: 70%Experimentation: 10%

**Recommended Background or Pre-Requisites:** Some background or experience with data analysis in python would be beneficial

Additional Safety Training required: Normal office/computer working. If lab work is required:'- SCAPA laser and radiation safety Suitable for: BSc, Mphys Notes:

### Optimising ion acceleration from the SCAPA laser using harmonic generation

#### Project ID: RG1

#### **Division:** Plasma **Email:** ross.gray@strath.ac.uk

Primary Supervisor: Ross Gray Secondary Supervisor(s): Robbie Wilson, Paul McKenna

**Project Background:** The SCAPA facility at Strathclyde houses one of the worlds most powerful lasers and is actively being used to develop sources of high energy ion beams from laser-plasma interactions. These beams have promising applications for new cancer therapies due to their unique properties such as ultra-short bunch durations. A key challenge in this research is to measure important plasma parameters such as the plasma density profile which is essential in controling the acceleration process. One route to achieving this is by using measurements of harmonic emission from the plasma which tell us about important processes happening during the laser-plasma interaction. Accurate plasma diagnostics enable the fine-tuning of laser parameters, ensuring consistent and controlled ion beam generation. In this project we will analyse data previously taken on SCAPA to determine and understand the correlation between harmonic emission and plasma expansion. In addition to analysing previous data there will be opportunities during the project to take part in experiments on SCAPA and run simulations in support of the analysis.

**Aim:** Measure the correlation between harmonic generation and plasma expansion measured on the SCAPA facility

Tasks: 1) Data analysis using Python of existing data sets measured on SCAPA

2) Simulation/modelling of harmonic emission

3) Potential to design new diagnostic measurements to run during a SCAPA experiment

#### **Key References:**

[1] Wiggins, S. M., et al. "Application programmes at the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)." Relativistic Plasma Waves and Particle Beams as Coherent and Incoherent Radiation Sources III. Vol. 11036. SPIE, 2019.

[2] Daido, Hiroyuki, Mamiko Nishiuchi, and Alexander S. Pirozhkov. "Review of laser-driven ion sources and their applications." Reports on progress in physics 75.5 (2012): 056401.

[3] Zepf, Matthew, et al. "Role of the plasma scale length in the harmonic generation from solid targets." Physical Review E 58.5 (1998): R5253.

Project Composition:Theory: 10%Computation: 40%Experimentation: 50%

**Recommended Background or Pre-Requisites:** Some background or experience with data analysis in python would be beneficial

Additional Safety Training required: Normal office/computer working. If lab work is required:

- SCAPA laser and radiation safety Suitable for: BSc, MPhys Notes:

### Designing a laser-driven proton beamline to irradiate cancer cells

#### Project ID: RG2

**Division:** Plasma **Email:** ross.gray@strath.ac.uk

Primary Supervisor: Ross Gray Secondary Supervisor(s): Ewan Dolier, Paul McKenna

**Project Background:** The LhARA project is a national programme to develop an ion therapy research facility to study new methods of cancer treatment. The first radiobiology experiments for that project will be performed using the SCAPA facility based at Strathclyde with one of the worlds most powerful lasers. Through laser-plasma interactions we will accelerate a beam of high energy ions. This ion beam must be focused and guided to sample cancers cells which will be irradiated for testing and demonstration. The laser-plasma interaction also produces beams of x-rays and electrons which must be removed so that the cells are only irradiated by ions. In this project, we will develop a model of laser-driven ion acceleration and the key components of the beamline. We will then optimise the design and placement of a dipole magnet which removes electrons from the particle beam while directing the ions to the desired sample. This project will make an important contribution to the development of an ion beamline in SCAPA and toward the first radiobiology experiments for future cancer therapies.

**Aim:** Model and design key components of a laser-driven proton beamline used for radiobiology experiments. **Tasks:** 1) Developing a basic model of laser-driven ion acceleration

2) Developing a basic model of ion and electron deflection in a dipole magnet

3) Optimisation of magnet design and positioning to produce desired beam parameters

#### **Key References:**

[1] Wiggins, S. M., et al. "Application programmes at the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)." Relativistic Plasma Waves and Particle Beams as Coherent and Incoherent Radiation Sources III. Vol. 11036. SPIE, 2019.

[2] Aymar, Galen, et al. "LhARA: the laser-hybrid accelerator for radiobiological applications." Frontiers in Physics 8 (2020): 567738.

[3] Daido, Hiroyuki, Mamiko Nishiuchi, and Alexander S. Pirozhkov. "Review of laser-driven ion sources and their applications." Reports on progress in physics 75.5 (2012): 056401.

Project Composition:Theory: 40%Computation: 50%Experimentation: 10%

**Recommended Background or Pre-Requisites:** Some background or experience with data analysis in python would be beneficial

Additional Safety Training required: Normal office/computer working Suitable for: BSc, Mphys Notes:

### Strong field QED

Project ID: AN1 Primary Supervisor: Adam Noble Secondary Supervisor(s): Brian McNeil Division: Plasma Email: adam.noble@strath.ac.uk

**Project Background:** Quantum electrodynamics is perhaps the most precisely verified theory in all of physics. However, it has been probed almost exclusively in the weak field limit, where interactions between charged particles and electromagnetic fields can be treated perturbatively. Developments in laser technology mean that we can now reach regimes where such perturbative approximations break down, and we need to find new approaches to making predictions. This project will explore a variety of descriptions of particle-field interactions, and apply them in contexts relevant to future experiments.

**Aim:** To develop models of the quantum interactions of charged particles with intense electromagnetic fields. **Tasks:** Investigate the field equations for relativistic quantum particles in strong electromagnetic fields. Couple these fields to Maxwell's equations to generate a self-consistent system. Analyse these systems in the context of laser-plasma interactions and/or free electron lasers.

#### **Key References:**

[1] Seipt, "Volkov States and Non-linear Compton Scattering in Short and Intense Laser Pulses," http://dx.doi.org/10.3204/DESY-PROC-2016-04/Seipt

[2] Heinzl and Ilderton, "Exact Classical and Quantum Dynamics in Background Electromagnetic Fields," Phys. Rev. Lett. 118, 113202 (2017).

[3]

Project Composition:	Theory: 75%	Computation: 25%	<b>Experimentation:</b> 0%
	111001 91 7 370		Experimentation 070

**Recommended Background or Pre-Requisites:** This project will appeal to students with an interest in electrodynamics, quantum physics and relativity, and who are mathematically confident.

#### Additional Safety Training required:

Suitable for: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching Notes:

### Nonlinear electrodynamics

Project ID: AN2 Primary Supervisor: Adam Noble Secondary Supervisor(s): Dino Jaroszynski Division: Plasma Email: adam.noble@strath.ac.uk

**Project Background:** Maxwell's equations in vacuum are famously linear, so solutions can be superposed. This means that electromagnetic waves are insensitive to the presence of background magnetic fields, and there is no photon-photon interaction. According to quantum theory, though, the vacuum is teeming with virtual particles, which can mediate a nonlinear interaction between electromagnetic fields. The effects of nonlinear electrodynamics have not yet been observed, but remain an active area of theoretical and experimental investigation.

**Aim:** To understand the concepts of nonlinear generalisations of Maxwell's equations, and investigate observable signatures.

**Tasks:** Reviewing the various models of nonlinear electrodynamics. Determining the behaviour of light waves propagating across various electromagnetic backgrounds. Identifying and exploring new observable signatures by which nonlinear effects may be probed.

#### **Key References:**

[1] Fouché, Battesti, and Rizzo, "Limits on nonlinear electrodynamics," Phys. Rev. D 93, 093020 (2016).

[2] Marklund and Shukla, "Nonlinear collective effects in photon-photon and photon-plasma interactions," Rev. Mod. Phys. 78, 591 (2006).

[3] Macleod, Noble, and Jaroszynski, "Cherenkov radiation from the quantum vacuum," Phys. Rev. Lett. 122, 161601 (2019).

Project Composition: Th	neory: 70% Computation	<b>Experimentation:</b> 0%
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**Recommended Background or Pre-Requisites:** This project will appeal to students with a strong mathematical background and an interest in fundamental questions in theoretical physics.

#### Additional Safety Training required:

Suitable for: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching Notes:

### Radiation reaction

Project ID: AN3

Primary Supervisor: Adam Noble Secondary Supervisor(s): Dino Jaroszynski **Division:** Plasma **Email:** adam.noble@strath.ac.uk

**Project Background:** Electromagnetic fields cause charged particles to accelerate, and accelerating charges emit radiation. Combining these two effects should lead to a self-consistent description of the motion of charged particles. However, the resulting equation exhibits highly unphysical behaviour: particles can accelerate rapidly in the absence of applied forces, or respond to fields that have not yet been applied. With recent technological advances, understanding this radiation reaction has become a pressing matter. This project will explore the various attempts to overcome these issues, and make physically reliable predictions in experimentally relevant conditions.

**Aim:** To understand the conceptual challenges of describing radiating particles, and analyse its effect on upcoming experiments.

**Tasks:** Investigate the origins of the unphysical predictions of radiation reaction. Critically analyse the proposed solutions and alternative models. Determine the behaviour of electrons in situations where radiation reaction is significant.

#### **Key References:**

[1] Burton and Noble, "Aspects of electromagnetic radiation reaction in strong fields," Contemp. Phys. 55, 110 (2014).

[2] Landau and Lifshitz, "The Classical Theory of Fields (Course of Theoretical Physics, Vol. 2)," 4th ed., Butterworth-Heinemann, Oxford, 1987.

[3] Kravets, Noble, and Jaroszynski, "Radiation reaction effects on the interaction of an electron with an intense laser pulse," Phys. Rev. E 88, 011201(R) (2013).

Project Composition:Theory: 70%Computation: 30%Experimentation: 0%

**Recommended Background or Pre-Requisites:** This project will appeal to mathematically-minded students with an interest in long-standing open problems.

Additional Safety Training required:

**Suitable for:** MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching **Notes:** 

### Stochastic particle heating of charged particles by plasma waves

Project ID: BE1 Primary Supervisor: Bengt Eliasson Secondary Supervisor(s): Kevin Ronald Division: Plasma Email: bengt.eliasson@strath.ac.uk

**Project Background:** Plasmas are ubiquitous in space and laboratory. The Earth is surrounded by a plasma layer, the so-called ionosphere, which shields us from radiation and energetic particles from the sun, and in the laboratory, plasmas are artificially created and studied with application to magnetic confinement fusion and basic research. A plasma is an ionised gas in which there are free electrons and ions so that the gas is electrically conducting. The Earth's ionosphere is magnetized by the geomagnetic field, and in the laboratory, an external magnetic field is used to confine the plasma and prevent it from escaping to the walls. The acceleration of charged particles by plasma waves can lead to chaotic motion of the particles and a rapid heating of the magnetised plasma due to the complicated motion of the particles. This is important for heating of particles in the laboratory, in magnetic confinement fusion devices, in the solar corona, in the Earth's ionosphere, etc., where collisions between particles are relatively rare. Stochastic heating is therefore different from Ohmic heating which is due to collisions between particles.

**Aim:** To study rapid heating of an ionised gas (plasma) by the chaotic motion of particles in a plasma wave. **Tasks:** Literature study of the topic. Initial simulations of stochastic heating using the code (in Matlab) provided by the supervisor Study stochastic heating and calculate statistical quantities such as temperature from a distribution of particles.

#### **Key References:**

[1] J. M. McChesney, R. A. Stern, and P. M. Bellan (1987) Observation of fast stochastic ion heating by drift waves, Phys. Rev. Lett. 59, 1436-1439.

[2] J. M. McChesney, R. A. Stern, and P. M. Bellan (1987) Observation of fast stochastic ion heating by drift waves, Phys. Rev. Lett. 59, 1436-1439.

[3] Najmi, A., B. Eliasson, X. Shao, G. M. Milikh, and K. Papadopoulos (2016), Simulations of ionospheric turbulence produced by HF heating near the upper hybrid layer, Radio Sci., 51, 704-717, doi:10.1002/2015RS005866.

Project Composition:	<b>Theory:</b> 50%	Computation: 50%	Experimentation: 0%
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**Recommended Background or Pre-Requisites:** Experience in simulations using Matlab (or any other programming language) and good theoretical skills are beneficial.

Additional Safety Training required: No special training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes:

### Ion Channel Laser with Large Oscillation Amplitude

#### Project ID: BEr1

Division: Plasma Email: bernhard.ersfeld@strath.ac.uk

Primary Supervisor: Bernhard Ersfeld Secondary Supervisor(s): Dino Jaroszynski

**Project Background:** The ion channel laser (ICL) is a proposed device for generating coherent radiation, similar to the free-electron laser (FEL), but much more compact. In the FEL, a relativistic electron beam radiates due to periodic deflection by the magnetic field of an undulator, whereas in the ICL electrons oscillate in the electrostatic field of a channel in plasma from which background electrons have been expelled (by an intense laser pulse or a relativistic particle beam). An important difference is that an efficient ICL requires oscillation amplitudes in excess of the electron beam width, which reduces the overlap with the emitted radiation and leads to non-linear effects, which are the subject of this investigation.

Aim: The project aims to investigate, analytically and numerically, effects of large oscillation amplitudes in ion channel lasers, e.g., harmonic generation and correlations between longitudinal and transverse electron motion. **Tasks:** Familiarise with Key Ref. 1 (below); literature review; familiarise with existing C code for numerical work Extend theory to include non-linear terms/ harmonics; implement corresponding terms in C code; produce and analyse numerical results; prepare presentation; write ~30-page report.

#### **Key References:**

[1] : B. Ersfeld et al., "The ion channel free-electron laser with varying betatron amplitude", New Journal of Physics 16 (9), 093025 (2014)

[2]

[3]

**Project Composition:** 

Theory: 50%

**Computation:** 50%

**Experimentation:** 0%

**Recommended Background or Pre-Requisites:** Knowledge in the following areas would be advantageous: wave propagation, Fourier theory; computer programming (C or similar).

Additional Safety Training required: No safety training required Suitable for: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching Notes:

### A coherent synchrotron source based on a laser-plasma wakefield accelerator

#### Project ID: DAJ1

**Division:** Plasma Email: d.a.jaroszynski@strath.ac.uk

Primary Supervisor: Dino Jaroszynski Secondary Supervisor(s): Antoine Maitrallain, Enrico Brunetti

Project Background: Laser wakefield acceleration in plasma (1) is a new scheme to accelerate particles, which enables bunch properties hitherto not achievable with conventional accelerators. Moreover, this type of accelerator can sustain accelerating fields 3-4 orders of magnitude higher than in a conventional RF accelerator, hence reducing the footprint of facilities substantially, which provides a unique source of electrons and electromagnetic radiation. Beams from laser wakefield accelerators have mono-energetic energy spectra at relatively high-energy and durations of approximately one femtosecond (10^-15s). Taking advantage of these extremely short bunches it is possible to directly produce coherent radiation using an undulator (2,3), which provides a unique compact femtosecond source of XUV coherent radiation.

Aim: The project will involve theoretical and numerical calculations (using software packages and purpose written routines) to study the evolution of the electron bunch properties during its propagation through the undulator and the characteristics of the radiation emitted.

Tasks: Literature review and in depth understanding of the field, familiarise with the codes used in the group, compare results with theory and potentially explain differences obtained Study bunch duration effects, space charge and energy effects on the radiation emitted after the undulator

#### **Key References:**

[1] Esarey E, Schroeder CB, Leemans WP. Physics of laser-driven plasma-based electron accelerators. Rev Mod Phys. 2009 Aug 27;81(3):1229-85.

[2] Schlenvoigt H-P, et al. A compact synchrotron radiation source driven by a laser-plasma wakefield accelerator. Nat Phys. 2008 Feb;4(2):130–3.

[3] D. A. Jaroszynski, et al., Coherent startup of an infrared free-electron laser, Phys. Rev. Lett. 71, 3798, 1993

Project Composition:	<b>Theory:</b> 0%	Computation: 0%	Experimentation: 0%
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Recommended Background or Pre-Requisites: Knowledge of Fortran or C++, PYTHON, MATLAB etc., good marks in a theoretical course and/or numerical simulation.

Additional Safety Training required: No special training required Suitable for: MPhys, BSc, BSc Maths and Physics

Notes: More than one student can take this project

### Semiconductor in your Backpack. Primary Outreach activity for Young Strathclyder.

#### Project ID: HLV1

**Division:** Physics Education **Email:** Helen.vaughan@strath.ac.uk

Secondary Supervisor(s): Carol Trager-Cowan

Primary Supervisor: Helen Vaughan

**Project Background:** Public engagement activities are an excellent way to connect the general public with the science that goes on in universities. It can comprise museum displays, posters, websites, guest lectures, popular science books and tours to name a few. Whilst these informal learning opportunities are enriching to those access to it, schools-centred science outreach programmes have the potential to make STEM and access to higher education more equitable. In particular, some STEM outreach activities have been shown to provide a wide range of role models that challenge a pupil's beliefs of what it is to be a scientist [1] and others, when designed thoughtfully, can change attitude to science in the community [2].

The Young Strathclyder Scheme [3] aims to widen access to Higher Education by providing enriching hands-on activities run by undergraduate mentors. This project will create and evaluate hands-on outreach materials suitable for the Young Strathclyder Scheme.

**Aim:** To design, create and evaluate a 45 minute hands-on activity/session linked to departmental research that inspires primary aged pupils about physics.

**Tasks:** Semester 1: undertake a literature review to assess what inspires young people about STEM and how to create effective public engagement activities, learn about ethical approval and evaluating outreach activities [3b], investigate the research undertaken by the Nanoscience to assess whether it can be communicated successfully to a non-specialist audience, collaborate with researchers to design outreach activity, develop evaluation method, apply for ethical approval\* (\*MUST be completed before end of Nov 2023),

Semester 2: ethical approval successful, create lesson plan and resources for the outreach activity including a teacher guide, test the materials (via delivery of the activity to suitable audience\*\*), collect and analyse evaluation data and use it to improve initial materials.

(Please note: whilst the activity should be delivered as part of the evaluation, there is no requirement that the project student has to deliver it if they don't want to).

#### **Key References:**

[1] Catherine L Muller et al 2013 Phys. Educ. 48 176 https://iopscience.iop.org/article/10.1088/0031-9120/48/2/176#artAbst

[2] Gall, A. J., Vollbrecht, P. J., & Tobias, T. (2020). Developing outreach events that impact underrepresented students: Are we doing it right?. European Journal of Neuroscience, 52(6), 3499-3506.

[3] News Article: Young Strathclyder Launched

https://www.strath.ac.uk/whystrathclyde/news/2023/youngstrathclyderschemefostersloveoflearning/ 3b Engineering UK, Using surveys to evaluate your STEM outreach programme

https://www.tomorrowsengineers.org.uk/media/it3aprin/evaluating-using-surveys.pdf

Project Composition:	<b>Theory:</b> 50%	Computation: 0%	Experimentation: 50%
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**Recommended Background or Pre-Requisites:** Succesful completion of Year 3. This project will require students to learn and use research skills associated with social sciences. It highly recommended for students interested in teaching or other careers in communication and those that like to take

#### Additional Safety Training required: As required by the activity designed. Ethical Approval training

Suitable for: BSc, BSc Maths and Physics

**Notes:** Please note: whilst the activity should be delivered as part of the evaluation, there is no requirement that the project student has to deliver it if they don't want to.

# **Optics Division**

### Grating magneto-optical trap modelling

Project ID: AA1 Primary Supervisor: Aidan Arnold **Division:** Optics **Email:** aidan.arnold@strath.ac.uk

Secondary Supervisor(s): Paul Griffin, Oliver Burrow

**Project Background:** Magneto-optical traps are ubiquitous in many atomic physics experiments, providing a dense source of ultracold atoms which can be utilised to obtain ultra-precise measurements [1]. However, such traps require six input laser beams and thereby suffer from optical complexity which can inhibit portable applications. We have pioneered the use of grating magneto-optical traps to circumvent this problem [2-3]. **Aim:** To model the acceleration in different kinds of magneto-optical trap to see how atom number scales with a wide variety of control parameters, ideally comparing to experiments.

**Tasks:** Cover the background of atom trapping, with a literature review. Integrate the computational acceleration via differential equations to calculate atomic trajectories. Compare and contrast existing trap strategies, optimising against e.g. atom number to find the ideal relaisitc experimental parameters.

#### **Key References:**

[1] 10.1103/PhysRevLett.59.2631[2] 10.1364/OE.23.008948[3] 10.1038/NNANO.2013.47

Project Composition:	Theory: 40%	Computation: 60%	Experimentation: 0%
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**Recommended Background or Pre-Requisites:** Proficiency in programming e.g. Mathematica or Matlab or Python

Additional Safety Training required: None Suitable for: Mphys Notes:

### Studies of the interaction of laser light with atoms

#### Project ID: AA2

Division: Optics Email: aidan.arnold@strath.ac.uk

Primary Supervisor: Aidan Arnold Secondary Supervisor(s): Erling Riis, Paul Griffin

**Project Background:** The project has a lot of flexibility, and one can study e.g. the Beer-Lambert Law (and its generalisation) by both imaging the fluorescence (spontaneous emission) as well as studying the laser light transmitted through a rubidium atom vapour cell. Key variables include the beam initial intensity, beam shape, and cell temperature. Possible extensions are the investigation of multiple beam interference, and dynamically scanned beams. The project requires a student with good experimental and analysis skills.

**Aim:** You will make a thorough investigation of how laser light is absorbed and emitted by atoms. **Tasks:** Atomic physics and laser background, with literature review.

Key References:

[1] 10.1364/OE.21.022215

[2] https://arxiv.org/abs/2307.06229 [3] 10.1088/0953-4075/41/15/155004

Project Composition:	<b>Theory:</b> 15%	Computation: 15%	Experimentation: 70%

**Recommended Background or Pre-Requisites:** PH380 lab skills, Proficiency in programming e.g. Mathematica or Matlab or Python.

Additional Safety Training required: Lasers Suitable for: Mphys Notes:

#### Laser cooling experiments

Primary Supervisor: Aidan Arnold

Project ID: AA3

**Division:** Optics **Email:** aidan.arnold@strath.ac.uk

Secondary Supervisor(s): James McGilligan

**Project Background:** This experiment involves a vast array of lasers, optics, vacuum equipment, computer control and electronics – there is a steep learning curve. Normally reserved for PhD projects, but available for hard-working 2-year (MPhys) project students.

**Aim:** This project involves performing experiments on some of the coldest material in the known universe – at chilly microKelvin temperatures. You will observe and manipulate billion-atom gases that can be seen on a video camera.

**Tasks:** Atomic physics, lasers, and laser cooling background, with literature review and experimental skill sessions.

#### **Key References:**

[1] https://doi.org/10.1364/OPTICA.5.000080

[2] https://eqop.phys.strath.ac.uk/author/dr-aidan-arnold/ASAthesis.pdf

[3] 10.1364/OE.23.008948

Project Composition:Theory: 15%Computation: 15%Experimentation: 70%

**Recommended Background or Pre-Requisites:** PH380 lab skills, Proficiency in programming e.g. Mathematica or Matlab or Python.

Additional Safety Training required: Lasers Suitable for: Mphys Notes:

### Structured Light in Ultracold Atomic Mixes

Project ID: AMY1

**Division:** Optics **Email:** alison.yao@strath.ac.uk

Primary Supervisor: Alison Yao Secondary Supervisor(s): Grant Henderson

**Project Background:** Atromtronics is a novel quantum technology, developing more capable currents made of ultracold atoms rather than electrons. At Strathclyde, we investigate using light with orbital angular momentum (OAM) to maniupulate BEC atoms and potentially realise such currents. We have previously shown that OAM-carrying light can reliably manipulate the dynamics of ultracold single-species atoms (Caesium). In this project you will extend this work to other single-species, and novelly dual-species, ultracold atomic configurations. **Aim:** Investigating the use of light carrying orbital angular momentum to create complex structures in mixed-species ultracold atoms.

**Tasks:** 1. Understand the complex mathematical model describing the coupled evolution of the light-atom system for single-species condensates. 2. Using pre-existing numerical codes, compare existing results for Caesium with other single-species condensates. 3. Extend the numerical model to consider dual-species condensates. 4. Building on pre-existing numerical codes, simulate the formation mechanism for atomtronic current generation in dual-species ultracold atomic mixes and compare to their single-species equivalents. **Key References:** 

[1] GW Henderson, GRM Robb, GL Oppo, AM Yao, "Control of light-atom solitons and atomic transport by optical vortex beams propagating through a Bose-Einstein Condensate", Phys. Rev. Lett. 129, 073902 (2022).
 [2] L Aming, D Andrewer, M Paching, L D Prentyte, L C Kurch, A Minnueri, and Wave, Klipping, "Atomic propagating time in a singulation of the second seco

[2] L Amico, D Anderson, M Boshier, J-P Brantut, L-C Kwek, A Minguzzi, and W von Klitzing, "Atomtronic circuits: From many-body physics to quantum technologies", Rev. Mod. Phys. 94, 041001 (2022).

[3] AM Yao, MJ Padgett, "Orbital angular momentum: origins, behavior and applications", Adv. Opt Photon 3, 161 (2011)

**Project Composition:** 

**Theory: 30%** 

**Computation:** 70%

**Experimentation:** 0%

**Recommended Background or Pre-Requisites:** Codes provided will be in Python language: previous experience not essential and support will be offered.

Additional Safety Training required: Suitable for: MPhys, BSc, BSc Maths and Physics Notes:

### The Gutzweiller wavefunction

Project ID: BH1

Division: Optics Email: benjamin.hourahine@strath.ac.uk

Primary Supervisor: Ben Hourahine Secondary Supervisor(s): Peter Kirton

**Project Background:** Quantum mechanics is straightforward for collections of single particles, these can be solved independently and their solutions combined to make a simple but very approximate many-particle wavefunction. Truely many-particle wavefunctions are in general much more difficult, but can be approximated. One such approach is to project the states of single particles onto a many-body configurations and adjust the projection so as to minimize the energy. This project will test such "Gutzwiller" projection for a model system. **Aim:** Investigate the Gutzwiller wavefunction for a simple system and adapting the description for two-particle density matrices.

**Tasks:** 1. Understand the Gutzweiller approach for the simplest 2-particle case of the hydrogen molecule 2. Learn about one and two body density matrices 3. Write equations for Gutzweiller projections using density matrices 4. apply to the H2 molecule and if time permits more complicated cases.

### **Key References:**

[1] "Marting Gutzweiller and his wavefunction" https://michaelberryphysics.wordpress.com/wp-content/uploads/2013/07/berry447.pdf Accessed 04/08/24

[2] Gebhard "Gutzwiller wave functions for correlated electrons: theory and applications", Philosophical Magazine, 86:13-14, 1847 (2006)

[3] Bünemann, Gebhard, Schickling and Weber, Numerical minimisation of Gutzwiller energy functionals. Phys. Status Solidi B, 249: 1282 (2012).

Project Composition:	<b>Theory:</b> 70%	Computation: 30%	<b>Experimentation:</b> 0%
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Recommended Background or Pre-Requisites: Good performance in the quantum part of PH384

Additional Safety Training required: N/A

**Suitable for:** MPhys, MPhys Adv. Research, BSc Maths and Physics **Notes:** 

### Finding the 'perfect' atomic population

Project ID: BH2

Primary Supervisor: Ben Hourahine Secondary Supervisor(s): Oliver Henrich **Division:** Optics **Email:** benjamin.hourahine@strath.ac.uk

**Project Background:** The probability density of wavefunctions are continuous function in space, but for systems consisting of atoms, deciding which fraction of the probability density is associated with each atom is an unsolved problem. This is partly because there are too many solutions! There is an infinite number of ways to cut the probability up into separate atomic contributions, but there are problems with most of the suggested recipes. This project will try to fix a "near miss" called Modified Mulliken populations, to give them better formal behaviour while trying to retain their simplicity.

**Aim:** Design a new atomic population that is both simple enough to be useful and also follows a set of correct limits.

**Tasks:** 1. Learn about the main types of atomic partial populations 2. Investigate the shortcommings of Mulliken and other population types 3. Design and test version of modified Mulliken that are local, electron conserving and give physically sensible local numbers of electrons 4) investigate how external potentials (for example electric fields) would couple with the new populations.

#### **Key References:**

[1] https://doi.org/10.1016/S0166-1280(99)00450-9

[2] https://pubs.acs.org/doi/10.1021/om950966x

[3] https://doi.org/10.1002/cphc.202000040

Project Composition:	<b>Theory:</b> 80%	Computation: 20%	<b>Experimentation:</b> 0%
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Recommended Background or Pre-Requisites: Good performance in the quantum part of PH384

#### Additional Safety Training required: N/A

**Suitable for:** MPhys, MPhys Adv. Research, BSc Maths and Physics, BSc Notes:

### Smart interpolation of oceanic data

Project ID: BH3

Division: Optics Email: benjamin.hourahine@strath.ac.uk

Primary Supervisor: Ben Hourahine Secondary Supervisor(s): David McKee

**Project Background:** Late data sets of ocean water composition and optical properties have been experimentally gathered due to their use in measuring environmental change. The data is only available for some compositional mixtures, so estimating the properties for unknown cases is important. A method, originally from geospatial statistics, called Krigging (or a related method called Gaussian processes regression) can provide estimates of missing values at arbitrary places and, crucially, gives an estimate of how accurate its predictions are. This project will use real oceanographic data to estimate values (with error bars) both for excluded data from the data set (method validation) and for unknown regions.

Aim: Investigate the use of Krigging to explore data and estimate missing values.

**Tasks:** 1) Introduction to simple Kriging 2) Familiarisation with suitable Python toolkit 3) Investigation of data variogram for test and then real data 4) Test and traing data set separation from real world data 5) Kriging of ocean bio-optical data

### **Key References:**

[1] https://doi.org/10.5194/essd-14-5737-2022

[2] Ma, Y.Z. (2019). Geostatistical Estimation Methods: Kriging. In: Quantitative Geosciences: Data Analytics, Geostatistics, Reservoir Characterization and Modeling. Springer, Cham. https://doi.org/10.1007/978-3-030-17860-4\_16

[3] Mirko Mälicke, Egil Möller, Helge David Schneider, & Sebastian Müller. (2021, May 28). mmaelicke/scikitgstat: A scipy flavoured geostatistical variogram analysis toolbox (Version v0.6.0). Zenodo. http://doi.org/10.5281/zenodo.4835779

Project Composition:

**Theory:** 50%

**Computation:** 50%

**Experimentation:** 0%

**Recommended Background or Pre-Requisites:** Good performance in PH282 or equivalent course covering basic statistics

Additional Safety Training required: N/A Suitable for: MPhys, MPhys Adv. Research, BSc Maths and Physics, BSc Notes:

### Computational Modelling of X-ray Free Electron Lasers

#### Project ID: BJM1

Division: Optics Email: b.w.j.mcneil@strath.ac.uk

Primary Supervisor: Brian McNeil Secondary Supervisor(s): Gordon Robb

**Project Background:** X-ray Free-Electron Lasers (XFELs), such as the LCLS at SLAC in California [1] and SACLA at Spring-8 in Japan, use high energy electron bunches, produced by particle accelerators, to generate intense pulses of X-rays within a long magnet called an undulator [2]. The spatial and temporal resolution available from the high brightness ultra-violet to x-ray pulses generated by these XFELs, is making feasible the observation and ultimately the potential to control ultra-fast, optionally non-linear processes in all forms of matter. With the ability to probe correlated electronic processes within atoms at short timescales, to measure how electrons and nuclei re-organise themselves, either individually within atoms due to external stimulus, during molecular bond making and breaking, or while undergoing subtle catalytic or biological processes, we can begin to unravel how all matter functions at this fundamental level. The supervisor of this project Dr Brian McNeil works closely with the UK's Accelerator Science and Technology Centre, along with international collaborators in this field. In the UK he is closely involved with the proposed CLARA facility based at Daresbury near Warrington [3]. Previously, good project students have obtained a summer studentship working there.

Aim: Predict new effects that can enhance or extend current XFEL performance.

**Tasks:** Starting from the basic working equations that describe the FEL process, the student will gain an understanding of how an XFEL works. You will then use numerical methods to solve the simplest case. This will involve solving equations describing the electron trajectories through the combined undulator and light fields, while simultaneously solving the equation that describes how the light field is driven by the electrons. Initially a code like MATLAB can be used. The student may wish to then use a lower-level language like Fortran, C or Java (your choice), to solve the same or extended equations describing further effects (e.g. harmonic light generation) and then present the solutions in a meaningful way using available plotting packages. The skills that you will learn are generic to a working theoretical/computational physicist and will prepare you well for a future career in this field. A good student should be able to take the analysis further and begin looking at more advanced topics. This will be like performing 'numerical experiments'.

#### **Key References:**

[1] https://portal.slac.stanford.edu/sites/lcls\_public/Pages/Default.aspx

[2] B.W.J. McNeil & N.R.Thompson, 'X-ray free-electron lasers', Nature Photonics, 4, 814, 2010

[3] http://www.stfc.ac.uk/ASTeC/Programmes/38749.aspx

**Project Composition:** 

**Theory:** 25%

Computation: 75%

**Experimentation:** 0%

**Recommended Background or Pre-Requisites:** 

Additional Safety Training required: No special training required Suitable for: MPhys, BSc, BSc (Maths Physics) Notes:

### The theory of X-ray Free electron Lasers

Project ID: BJM2

**Division:** Optics **Email:** b.w.j.mcneil@strath.ac.uk

Primary Supervisor: Brian McNeil Secondary Supervisor(s): Gordon Robb

**Project Background:** X-ray Free-Electron Lasers (XFELs), such as the LCLS at SLAC in California [1] and SACLA at Spring-8 in Japan, use high energy electron bunches, produced by particle accelerators, to generate intense pulses of X-rays within a long magnet called an undulator [2]. The spatial and temporal resolution available from the high brightness ultra-violet to x-ray pulses generated by these XFELs, is making feasible the observation and ultimately the potential to control ultra-fast, optionally non-linear processes in all forms of matter. With the ability to probe correlated electronic processes within atoms at short timescales, to measure how electrons and nuclei re-organise themselves, either individually within atoms due to external stimulus, during molecular bond making and breaking, or while undergoing subtle catalytic or biological processes, we can begin to unravel how all matter functions at this fundamental level. The supervisor of this project Dr Brian McNeil works closely with the UK's Accelerator Science and Technology Centre, along with international collaborators in this field. In the UK he is closely involved with the proposed CLARA facility based at Daresbury near Warrington [3]. Previously, good project students have obtained a summer studentship working there.

Aim: Predict new effects that can enhance or extend current XFEL performance.

**Tasks:** This project will involve the derivation of the working equations that describe the FEL process from the coupled Maxwell and Lorentz force equations. This will involve deriving equations that describe the trajectories of the relativistic electrons as they propagate through the undulating magnetic fields, how they consequently radiate light, how they then couple to this light, and how this coupling feeds back onto the electrons. Once derived, these non-linear equations can be analysed and simplified to obtain a set of coupled linear differential equations that can be solved analytically to obtain a solution. The skills that you will learn are generic to a working theoretical physicist and will prepare you well for a future career in any theoretical field. A good student may be able to take this theoretical analysis further and begin looking at more advanced topics involving a degree of research into areas that have previously not been well explored, and perhaps even predicting new and useful practical ideas.

#### **Key References:**

[1] https://portal.slac.stanford.edu/sites/lcls\_public/Pages/Default.aspx

[2] B.W.J. McNeil & N.R.Thompson, 'X-ray free-electron lasers', Nature Photonics, 4, 814, 2010

[3] http://www.stfc.ac.uk/ASTeC/Programmes/38749.aspx

**Project Composition:** 

**Theory:** 20%

Computation: 80%

**Experimentation:** 0%

**Recommended Background or Pre-Requisites:** 

Additional Safety Training required: No special training required Suitable for: MPhys, BSc, BSc (Maths Physics) Notes:

### Optimising Decoy State Satellite Quantum Key Distribution

#### Project ID: DO1

Division: Optics Email: daniel.oi@strath.ac.uk

Primary Supervisor: Daniel Oi Secondary Supervisor(s): Jasminder Sidhu

**Project Background:** In satellite quantum key distribution (QKD), the short duration of an overpass contrains the block size of raw signals that can be transmitted. The leads to finite statistical uncertainties of security parameters that may greatly effect the efficiency of secure cryptographic key generation from limited data. For the commonly used QKD method of Efficient BB84 with weak coherent pulse sources and decoy states, there are several optimisations that can be made, such as the choice of pulse intensities and probabilities that trade-off various finite-key effects. This project will look at the theory and numerical analysis of such protocols to derive optimum settings for satellite QKD.

**Aim:** To determine the optimum protocol parameters for Efficient BB84 utilising decoy state weak coherent pulse sources

**Tasks:** Literature review of SatQKD, theory of BB84 and decoy state protocols, construction of SatQKD model, simulation of QKD rates, optimisation and analysis of parameters in finite-key regime

#### **Key References:**

[1] Sidhu JS, Brougham T, McArthur D, Pousa RG, Oi DK. Finite key effects in satellite quantum key distribution. npj Quantum Information. 2022 Feb 16;8(1):18.

[2] Sidhu JS, Brougham T, McArthur D, Pousa RG, Oi DK. Finite key performance of satellite quantum key distribution under practical constraints. arXiv e-prints. 2023 Jan:arXiv-2301.

[3] Sidhu JS, Joshi SK, Gündoğan M, Brougham T, Lowndes D, Mazzarella L, Krutzik M, Mohapatra S, Dequal D, Vallone G, Villoresi P. Advances in space quantum communications. IET Quantum Communication. 2021 Dec;2(4):182-217.

**Project Composition:** 

**Theory:** 50%

Computation: 50%

**Experimentation:** 0%

**Recommended Background or Pre-Requisites:** Good results in Quantum and Mathematics courses. Programming experience (e.g. Python) an advantage but not necessary (can be picked up)

Additional Safety Training required: No special safety training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes: Open to 1 student

### Space Quantum Memories

Project ID: DO2 Primary Supervisor: Daniel Oi Secondary Supervisor(s): Thomas Brougham Division: Optics Email: daniel.oi@strath.ac.uk

**Project Background:** Global scale quantum entanglement distribution may require the use of space-based quantum memories (QMs) and quantum repeaters (QRs). QMs are currently under experimental development with a range of capabilities and constrainsts. Their characteristics will determine how they can be utilised to enhance the efficiency of transmitting entanglement over high-loss, short-duration space-ground links, such as their mode capacity, dephasing time, random access ability, and storage bandwidth. This project will model and analyse the use of QMs in satellite quantum memories in entanglement distribution via satellites **Tasks:** Literature review of quantum entanglement and quantum memories, theory of quantum repeaters and entanglement swapping, construction of space-QR link, simulation of entanglement distribution rates, analysis of QM characteristics

#### **Key References:**

[1] Gündoğan M, Sidhu JS, Henderson V, Mazzarella L, Wolters J, Oi DK, Krutzik M. Space-borne quantum memories for global quantum communication. arXiv preprint arXiv:2006.10636. 2020 Jun 18.

[2] Gündoğan M, Sidhu JJ, Oi DK, Krutzik M. Time-delayed single quantum repeater node for global quantum communications with a single satellite. arXiv preprint arXiv:2303.04174. 2023 Mar 7.

[3] Sidhu JS, Joshi SK, Gündoğan M, Brougham T, Lowndes D, Mazzarella L, Krutzik M, Mohapatra S, Dequal D, Vallone G, Villoresi P. Advances in space quantum communications. IET Quantum Communication. 2021 Dec;2(4):182-217.

Project Composition:Theory: 50%Computation: 50%Experimentation: 0%

**Recommended Background or Pre-Requisites:** Good results in Quantum and Mathematics courses. Programming experience (e.g. Python) an advantage but not necessary (can be picked up)

Additional Safety Training required: No special safety training required

Suitable for: MPhys, BSc, BSc Maths and Physics

**Notes:** Up to 2 students can take this project. The students will consider different quantum memory constraints and quantum repeater architectures

### Magnetic imaging with atomic magnetometers

Project ID: DH1

**Division:** Optics **Email:** d.hunter@strath.ac.uk

Primary Supervisor: Dominic Hunter Secondary Supervisor(s): Stuart Ingleby

**Project Background:** Magnetic imaging encompasses a diverse range of research fields including biomedical science, current density imaging, and concealed object detection, to name a few. Such applications require sensitive instrumentation capable of resolving the spatial and temporal properties of the magnetic sources of interest. Atomic magnetometers provide a sensitive platform for these magnetic imaging applications over a wide range of spatial resolutions.

Aim: To develop magnetic imaging platforms using optically pumped magnetometers.

**Tasks:** The project aims to develop and characterise an imaging system. Once realised, the system can be integrated with OPM technology to conduct magnetic imaging measurements. The candidate will gain experience in laser operation, optics, control instrumentation, and data analysis.

#### **Key References:**

[1] [1] D. Hunter et. al., "Free-induction-decay magnetometer based on a microfabricated Cs vapor cell," Phys. Rev. Appl. 10, 014002 (2018).

[2] [2] D. Hunter et al., 'Free-induction-decay magnetic field imaging with a microfabricated Cs vapor cell,' Opt. Express 31, 33582-33595 (2023)

[3] [3] D. Budker et. al., "Optical magnetometry," Nat. Phys. 3, 227-234 (2007).

Project Composition:Theory: 10%Computation: 30%Experimentation: 60%

**Recommended Background or Pre-Requisites:** The main criteria are that you are keen to work on experiments and as part of a team.

Additional Safety Training required: Standard safety training as part of EQOP group, including lasers and electronics.

**Suitable for:** MPhys, BSc, BSc Maths and Physics **Notes:** The project is suitable for 2 students

### Design, Construction and Benchmarking of a Fizeau Wavemeter

Project ID: EH1

**Division:** Optics **Email:** elmar.haller@strath.ac.uk

Primary Supervisor: Elmar Haller Secondary Supervisor(s): Kali Wilson

**Project Background:** The Fizeau Wavemeter is a real-time laser-wavelength measuring instrument for use with pulsed or CW lasers. The instrument contains a static Fizeau interferometer which is illuminated by the laser. The fringe pattern of the interferometer is recorded by a camera and analysed by a microprocessor or small computer to determine the wavelength of the illuminating laser. The goal of the project is to build a wavemeter yourself for the use in our labs. The construction will be based on existing proposals.

Aim: Build a device to measure the wavelengths of laser light and determine its properties.

**Tasks:** (1) Understand the working principles of a Fizeau Wavemeter and compare design proposals. (2) Build the Wavemeter mostly with existing commercial components. Design missing components with CAD software (Autodesk Inventor).

(3) Write software with Python or Matlab to analyse the camera images and determine the wavelength of the laser light. (4) Create a test protocol to characterize the wavemeter and the diode laser.

#### **Key References:**

[1] https://www.moglabs.com/fizeau-wavemeter (commertial product)

[2] https://doi.org/10.1364/AO.25.001339 (proposal)

[3] https://doi.org/10.1364/AO.27.003656 (proposal)

Project Composition:	<b>Theory:</b> 20%	Computation: 30%	Experimentation: 50%
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Recommended Background or Pre-Requisites: Knowledge of optics, atoms physics, photonics.

Additional Safety Training required: yes Suitable for: MPhys, BSc, BSc Maths and Physics Notes:

### Jamming-free Quantum LIDAR

Project ID: JP1

Primary Supervisor: Jonathan Pritchard Secondary Supervisor(s): Andre Oliveira **Division:** Optics **Email:** jonathan.pritchard@strath.ac.uk

**Project Background:** Optical rangefinding (LIDAR) provides an alternative technique to RADAR for locating and identifying targets, with use of optical wavelengths enabling higher directivity and improved spatial resolution. In the regime of low target reflectivity and high levels of background light, a quantum lidar source based on correlated photon pairs provides an advantage over classical detectors in performing confident target detection with orders of magnitude fewer signal photons, whilst being robust to intentional jamming as recently demonstrated in work at Strathclyde. This project aims to advance the current state of the art and build a portable system suitable for deployment in a realistic environment.

**Aim:** Develop a portable setup for practical demonstration of a quantum lidar robust to jamming. **Tasks:** (1) Initial tests of jamming-free quantum lidar using existing experimental setup (2) Design and build portable quantum LIDAR system (3) Implement real-time acquisition and processing of photon count data (4) Perform field-trials using realistic lighting conditions and targets.

#### **Key References:**

[1] M. Mateusz et al., Demonstration of quantum-enhanced rangefinding robust against classical jamming, Opt. Express 32, 2916-2928 (2024) https://doi.org/10.1364/OE.503619

[2] D.G. England et al., Quantum-enhanced standoff detection using correlated photon pairs, Phys. Rev. A 99, 023828 (2019) https://doi.org/10.1103/PhysRevA.99.023828

[3] H. Liu et al., Enhancing LIDAR performance metrics using continuous-wave photon-pair sources Optica 6, 1349 (2019) https://doi.org/10.1364/OPTICA.6.001349

Project Composition:Theory: 10%Computation: 30%Experimentation: 60%

**Recommended Background or Pre-Requisites:** Students should be comfortable with using Python. Recommended modules PH455 Topics in Photonics

Additional Safety Training required: Laser safety training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student can take this project.

### Quantum optimisation with Rydberg atoms

Project ID: JP2

**Division:** Optics **Email:** jonathan.pritchard@strath.ac.uk

Primary Supervisor: Jonathan Pritchard Secondary Supervisor(s): Gerard Pelegrí

**Project Background:** Neutral atom quantum computers [1] are a promising platform to perform optimisation tasks with applications in real-world problems [2]. A prominent example of this is the direct correspondence between the ground state of a set of Rydberg atoms trapped in tweezer arrays and the maximum independent set of a graph [3]. In this project, a motivated student will simulate a many-body Rydberg system and investigate different aspects of the optimal preparation of maximum independent set solutions by manipulating Rydberg atoms with laser pulses.

Aim: Investigate the use of Rydberg-atom quantum computers to find optimal solutions of graph problems. Tasks: (1) Perform literature review (2) Develop code to simulate time evolution in a many-body Rydberg system (3) Explore optimal ways to prepare the maximum independent set of a graph (4) If appropriate, compare the performance of the code on CPU vs GPU.

#### **Key References:**

[1] L. Henriet et. al., Quantum computing with neutral atoms, Quantum 4, 327 (2020) https://doi.org/10.22331/q-2020-09-21-327

[2] J. Wurtz et. al., Industry applications of neutral-atom quantum computing solving independent set problems, arXiv:2205.08500 https://doi.org/10.48550/arXiv.2205.08500

[3] S. Ebadi et. al., Quantum optimization of maximum independent set using Rydberg atom arrays, Science 376, 1209 (2022) https://doi.org/10.1126/science.abo6587

Project Composition:Theory: 50%Computation: 50%Experimentation: 0%

**Recommended Background or Pre-Requisites:** Students should be comfortable with using Python. Recommended modules PH462 Topics in Quantum Optics, PH459 Topics in Atomic Physics

Additional Safety Training required: No special training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student can take this project.

#### Quantum reservoir computing with neutral atoms

#### Project ID: JP3

**Division:** Optics **Email:** jonathan.pritchard@strath.ac.uk

Primary Supervisor: Jonathan Pritchard Secondary Supervisor(s): Dr Daniel Walker

**Project Background:** Reservoir computing is a machine learning technique which uses limited access to systems with complicated dynamics to classify data using significantly simplified training compared to the canonical case of, e.g., neural networks. Reservoir computing using quantum dynamical systems (quantum reservoir computing) is therefore an attractive prospect for quantum machine learning in the near term, as it places minimal requirements on the control of quantum hardware, and sidesteps the "barren plateau" problem found in training more conventional quantum machine learning models. Arrays of neutral atoms trapped in optical tweezers are a very promising platform for quantum computing in general, and lend themselves to the task of quantum reservoir computing due to their excellent scalability, and flexible and high-fidelity control through the long coherence times of atomic ground states and the robust interaction between atomic Rydberg states. **Aim:** Explore strategies to perform quantum reservoir computing using current and near-term neutral atom quantum computing hardware.

**Tasks:** (1) Review literature to become familiar with proposed implementations of quantum reservoir computing on neutral atom devices. (2) Simulate quantum reservoir computing on small instances of neutral atom quantum computers. (3) Investigate the performance of neutral atom quantum reservoir computing under different regimes of data encoding, readout postprocessing, and system dynamics.

#### **Key References:**

[1] Quantum computing with neutral atoms https://quantum-journal.org/papers/q-2020-09-21-327

[2] Large-scale quantum reservoir learning with an analog quantum computer

https://arxiv.org/abs/2407.02553v1

[3] Quantum Reservoir Computing Using Arrays of Rydberg Atoms

https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.3.030325

Project Composition:	<b>Theory:</b> 30%	Computation: 70%	<b>Experimentation:</b> 0%
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**Recommended Background or Pre-Requisites:** Students should be enthusiastic programmers, and preferably familiar with Python. This project will be most rewarding for students with a keen interest in quantum computing and machine learning, and who want to apply creativity in exploring reservoir comp

Additional Safety Training required: N/A Suitable for: MPhys, BSc, BSc Maths and Physics Notes: Suitable for 2 students

### Quantum Error Correction on Neutral Atom Arrays

#### Project ID: JP4

**Division:** Optics **Email:** jonathan.pritchard@strath.ac.uk

Primary Supervisor: Jonathan Pritchard

Secondary Supervisor(s): Johannes Kombe, Andrew Daley

**Project Background:** Rydberg-atoms in tweezer arrays have emerged as a very promising platform for quantum information processing due to their scalability, control, and long coherence times. However during computation errors inevitably will occur at the hardware level, establishing the need for error mitigation, and error correction schemes. Quantum error correction codes aim to protect quantum information from decoherence and dissipation. This project aims to explore the feasibility to use quantum error correcting protocols for a Rydberg-atom quantum computing platform, by looking at resource estimates, realistic code designs, and error thresholds.

**Aim:** Explorie the feasibility of quantum error correction schemes for a Rydberg-atom quantum computer. **Tasks:** (1) Perform extensive literature review (quantum error correction and Rydberg atom physics) (2) Become familiar with one of the available quantum simulators (QuTiP, QuEST, ...) (3) Perform resource estimation, and implement simulation of an error correction code to explore feasibility on a Rydberg device

#### **Key References:**

[1] J. Roffe, Quantum error correction: an introductory guide, Contemporary Physics 60, 3 (2019), DOI: 10.1080/00107514.2019.1667078

[2] L. Henriet et. al., Quantum computing with neutral atoms, Quantum 4, 327 (2020) https://doi.org/10.22331/q-2020-09-21-327

[3] I. Cong et al., Hardware-Efficient, Fault-Tolerant Quantum Computation with Rydberg Atoms, Phys. Rev. X 12, 021049 (2022) https://doi.org/10.1103/PhysRevX.12.021049

Project Composition:	Theory: 50%	Computation: 50%	<b>Experimentation:</b> 0%
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**Recommended Background or Pre-Requisites:** Students should be comfortable with using Python (and potentially C or Mathematica). Recommended modules PH462 Topics in Quantum Optics, PH459 Topics in Atomic Physics

Additional Safety Training required: N/A Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student can take this project.

### Holographic generation of 3D trapping potentials for cold-atom experiments.

#### Project ID: JP5

Division: Optics Email: jonathan.pritchard@strath.ac.uk

Primary Supervisor: Jonathan Pritchard Secondary Supervisor(s): Paul Schroff

**Project Background:** In many neutral atom quantum computing and simulation experiments, cold atoms are trapped in holographically-generated arrays of optical tweezers. Typically, these tweezers are created in a 2D plane, enabling to generate arbitrary 2D structures. Optical tweezer arrays are commonly generated using a phase-modulating spatial light modulator (SLM) that imprints a phase pattern onto the incident laser beam, allowing almost arbitrary control over the intensity profile of the light in the focal plane of a lens. Extending this approach from a 2D plane to three dimensions has been demonstrated [1, 2], however, these 3D geometries suffer from crosstalk between neighbouring traps located at different planes along the optical axis. Several algorithms that calculate the SLM phase pattern to generate three-dimensional light potentials have been developed [1-3], optimising trap uniformity and minimising crosstalk between planes.

Aim: Simulation and characterisation of 3D trapping potentials using phase-only holograms.

**Tasks:** Investigating suitable algorithms to calculate holograms for 3D trapping geometries. Implementation of computationally efficient methods to simulate the propagation of light in three dimensions. Characterisation of optical traps (e.g. uniformity, crosstalk between neighbouring traps in different planes, ...).

#### Key References:

[1] Barredo, D., Lienhard, V., de Léséleuc, S., Lahaye, T. & Browaeys, A. Synthetic three-dimensional atomic structures assembled atom by atom. Nature 561, 79–82 (2018).

[2] Pégard, N. C. et al. Three-dimensional scanless holographic optogenetics with temporal focusing (3D-SHOT). Nat Commun 8, 1228 (2017).

[3] Zhang, J., Pégard, N., Zhong, J., Adesnik, H. & Waller, L. 3D computer-generated holography by non-convex optimization. Optica 4, 1306–1313 (2017).

Project Composition: Theory: 50% Computation: 50% Experimentation: 0%

**Recommended Background or Pre-Requisites:** Students should be comfortable with using Python. Recommended modules PH455 Topics in Photonics

Additional Safety Training required: -

**Suitable for:** MPhys, BSc, BSc Maths and Physics **Notes:** One student can take this project. A laptop is required to run optical simulations.

### Quantum chaos and control in the dynamics of quantum computers

#### Project ID: PP1

# **Division:** Optics

Primary Supervisor: Pablo Poggi Secondary Supervisor(s): Peter Kirton Email: pablo.poggi@strath.ac.uk

Project Background: Quantum chaos deals with the dynamics of generic quantum systems in absence of constraints. It its known that chaos is strongly linked to aspects as diverse as the rapid generation of entanglement or the sensitivity of a system to an external perturbation. In applications like quantum computing, this diverse chaotic properties can be seen as a feature or a threat. This project will study how chaos arises in the dynamics of simple quantum systems, and how to use tools from quantum control theory to manipulate quantum chaotic behavior.

Aim: Exploring which aspects of chaos arise in the dynamics of simple quantum systems, and study how to control them for useful tasks in quantum computing

Tasks: Studying basic aspects of quantum chaos and quantum computing. Developing numerical tools to study dynamical properties of chaotic quantum systems. Learning about and applying quantum optimal control techniques to these systems.

#### **Key References:**

[1] Quantum Chaos and Quantum Computers: https://arxiv.org/abs/quant-ph/0006073

[2] Universally Robust Quantum Control: https://arxiv.org/abs/2309.14437

[3] Training Schrödinger's cat: quantum optimal control': https://link.springer.com/article/10.1140/epjd/e2015-60464-1

Project Composition:	<b>Theory:</b> 60%	Computation: 40%	<b>Experimentation:</b> 0%
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Recommended Background or Pre-Requisites: Programming in Python (alternatively Matlab or Julia) will be required. Strong background on quantum courses.

Additional Safety Training required: No special training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student can take this project.

### Laser spectroscopy for precision measurement of atomic transition frequencies.

#### Project ID: PG1

#### **Division:** Optics **Email:** paul griffin@strath.ac.uk

Primary Supervisor: Paul Griffin Secondary Supervisor(s): Prof Erling Riis Email: paul.griffin@strath.ac.uk

**Project Background:** The quantum mechanical model of atoms arose from experimental observations of atomic spectra. The evidence of strong lines inspired Bohr to develop a picture of quantised energy levels to explain the discrete spectra. To this day, experimental observations drive new discoveries and insights into the physical understanding of matter and the interaction with light.

A literature review of rubidium spectroscopy will quickly tell you that the natural linewidth of the main spectroscopic line at 780nm is 6 MHz, limited by the half-life of the excited state and time-energy uncertainty relation. However, measuring to this resoluton is extremely difficult – (most people won't read this far so I'm semi-safe in admitting that not only have I never measured to this resolution, I'm fairly sure that I don't know anyone who has). This is because of the many effects that broaden the line due to Doppler shifts, transit-time broadening, power broadening, magnetic gradients, ...)

In this project we will design a system that allows us to measure this transition in rubidium at the limit. **Aim:** This project will build a precision aparatus to measure atomic spectra at the limit of the Time-Energy uncertainty relation.

**Tasks:** The project will begin by developing practical experience of lasers and optical components. This will be supported by a literature review.

Experimental tasks will be focused on spectroscopy of the D2 line of rubidium, and eliminating broadening effects that have limited the obtainable resolution.

Critical data analysis will be an important aspect of the project.

### **Key References:**

[1] T. W. Hansch, A. L. Schawlow, and G. W. Series. "The spectrum of atomic hydrogen". Scientific American, 240, 72 (1979)

[2] C.E. Wieman, L Hollberg Using diode lasers for atomic physics Rev. Sci. Instrum. 62, 1–20 (1991)[3]

Project Composition:	Theory: 20%	Computation: 5%	Experimentation: 75%
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Recommended Background or Pre-Requisites: Project will develop skills in optics and atomic physics.

Project is suited to a student eager to work on experiments and with an interest in seeing an experiment through from initial planning through to final data analysis

Additional Safety Training required: Standard safety training as part of EQOP group, including lasers and electronics

**Suitable for:** MPhys, BSc, BSc Maths and Physics **Notes:** One student can take this project.

### Models of ultra-narrow linewidth lasing

Project ID: PK2

**Division:** Optics **Email:** peter.kirton@strath.ac.uk

Primary Supervisor: Peter Kirton Secondary Supervisor(s): Francesco Papoff

**Project Background:** In the simplest quantum model of a laser light and matter interact by the exchange of matter excitations for photons in the cavity. The noise associated with the process puts a limit on the linewidth of the emitted laser light. Recent proposals [1,2] have shown that by modifying this interaction, so that instead the matter couples to 'bare' photon operators, the noise can be greatly reduced, below the standard quantum limit. Using a combination of numerical simulations and analytical approximations we will investigate how this phenomena occurs and look into how the presence of other noise processes can affect it.

Aim: To develop full quantum descriptions of ultra-low noise lasers

Tasks: Understand the standard quantum description of a laser

Develop models of low linewidth lasers

Characterise the effects of different dissipation processes on the output light

#### **Key References:**

[1] Baker et al Nat Phys 17, 179 (2021)

[2] Liu et al Nat Commun 12, 5620 (2021)

[3]

Project Composition: Theory: 50%

**Computation:** 50%

**Experimentation:** 0%

**Recommended Background or Pre-Requisites:** Programming in python or julia will be required. Background from PH389 and PH388

Additional Safety Training required: Suitable for: MPhys, BSc, BSc Maths and Physics Notes:

### Understanding Phase Transitions with the Adiabatic Gauge Potential

#### Project ID: PK1

**Division:** Optics **Email:** peter.kirton@strath.ac.uk

Primary Supervisor: Peter Kirton

Secondary Supervisor(s):

**Project Background:** The adiabatic gauge potential (AGP) [1] was developed as tool for controlling the dynamics of quantum systems. It tells us how to change the Hamiltonian of a system such that it remains in a state that we want. In this project you will learn how this technique works and use a new numerical method [2] to calculate the AGP in complex quantum systems which exhibit phase transitions between states with different magnetic properties. This will allow us to understand which universal properties can be extracted from the AGP. **Aim:** To develop an understanding of how we can

Tasks: Understand what the AGP is and how to calculate it

Use the mAGPy library to calculate the AGP in simple systems

Find the AGP in many-body magnetic models to understand phase transitions

#### **Key References:**

[1] M. Kolodrubetz, D. Sels, P. Mehta and A. Polkovnikov, Physics Reports 697, 1 (2017)

[2] EDC Lawrence et al. ArXiv:2401.10985 (2024)

[3]

Project Composition:	<b>Theory:</b> 50%	Computation: 50%	Experimentation: 0%
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**Recommended Background or Pre-Requisites:** Programming in python will be required. Background from PH389 and PH388

# Additional Safety Training required:

Suitable for: MPhys, BSc, BSc Maths and Physics Notes:

### Demonstrations of Single Photon Experiments

Project ID: SK1

**Division:** Optics **Email:** stefan.kuhr@strath.ac.uk

Primary Supervisor: Stefan Kuhr Secondary Supervisor(s): Daniel Oi

**Project Background:** The production, measurement, and application of single photons and photon pairs are crucial for many quantum technology application such as quantum communication, sensing, and information processing. The workhorse technique is sponanteous parametric down conversion that produces pairs of correlated photons that may exhibit non-classical behaviour such as entanglement. Detecting single photons can be performed using Geiger-mode avalanche photo diodes (GM-APDs) together with time-taggers and coincidence counting. This project will utilise SPDC and GM-APDs to build experiments to demonstrate quantum optical phenomena with single photons.

**Aim:** To build and test a photon pair source and demonstrate fundamental quantum optics experiments **Tasks:** Review quantum theory of light, SPDC, single photon detection techniques. Set-up and characterise SPDC photon pair source and detection system. Construct and operate quantum optics experiments utilising heralded single-photon source. Compare modelled performance with observed data.

#### **Key References:**

[1] EDU-QOP1(/M) Quantum Optics Kit User Guide https://www.thorlabs.com/\_sd.cfm?fileName=MTN036012-D02.pdf&partNumber=EDU-QOP1

[2] References within Key Reference 1

[3]

Project Composition:Theory: 10%Computation: 10%Experimentation: 80%

Recommended Background or Pre-Requisites: Good results in Quantum and Lab courses

Additional Safety Training required: Laboratory safety training, especially Laser Safety, will provided Suitable for: MPhys, BSc, BSc Maths and Physics Notes: Open to 1 student

### A laser system for Rb spectroscopy

Project ID: TA1

Primary Supervisor: Thorsten Ackemann Secondary Supervisor(s): Paul Griffin Division: Optics Email: thorsten.ackemann@strath.ac.uk

**Project Background:** External cavity diode lasers (ECL) are a versatile and relatively inexpensive lasers source for addressing narrow atomic lines in the near infrared spectrum and are hence the established workhorse for quantum technologies based on alkaline atoms like Rb or Cs. These ECL are built from off-the-shelf laser diodes with optical feedback from a grating [1]. They are stabilized against frequency drifts via saturable absorption spectroscopy [2,3]. The project will set up two ECL for cooling and trapping of Rb atoms, set up the frequency stabilization and characterize their stability. Depending on progress, extensions in the direction of amplifying the ECL or other nonlinear optical investigations are possible.

**Aim:** Set up a tunable laser and frequency stabilization to enable spectroscopy and nonlinear optical measurements in Rb vapour

Tasks: setting up and aligning optical setup, small electronic soldering taks, understanding PDI controllers, data analysis

### Key References:

[1] Arnold et al., Rev Sci Instr 69, 1236 (1998); ibd. 72, 4477 (2001)

[2] Preston, Am J Phys 64, 1432 (1996)

[3] Kraft et al., Laser Phys Lett 1, 1(2004)

Project Composition:	<b>Theory:</b> 5%	Computation: 5%	<b>Experimentation:</b> 90%
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**Recommended Background or Pre-Requisites:** student should take PH445 Photonics and possibly PH453 solid state physics in sem 1, PH459 Atomic Physics in sem 2. Student need to be willing to undertake potentially tedious optical alignment tasks.

Additional Safety Training required: Laser safety Suitable for: MPhys, BSc, BSc Maths and Physics Notes:

### Spintronics in vertical-cavity gain structures

#### Project ID: TA2

**Division:** Optics **Email:** thorsten.ackemann@strath.ac.uk

Primary Supervisor: Thorsten Ackemann Secondary Supervisor(s): Konstantinos Lagoudakis

**Project Background:** The research field of spintronics aims at utilizing the carrier spin for applications in addition to the number of carriers as usual in electronics and semiconductor photonics [1,2]. However, electrical injection of spin polarized carriers is still limited to cryogenic temperatures or low temperatures in combination with a large magnetic field. At room temperature, optical pumping provides a convenient alternative to electrical injection since carrier spin and photon spin are coupled by angular momentum selection rules. III-V semiconductor gain media in vertical-cavity structures possess the necessary isotropy in the plane of the gain medium to investigate spin dependent effects. This project will look at surface emitting gain structures containing quantum well or quantum dots for the use in VECSELs, vertical-external cavity surface-emitting lasers. The measurements will start with analyzing the polarization properties of the photoluminescence in dependence on the polarization ellipticity of the optical pump field extending [3]. The final aim of the project is to achieve lasing.

**Aim:** to demonstrate spin memory in photoluminescence and potentially lasing in optically pumped quantum dot and quantum well vertical-cavity semiconductor gain structures

**Tasks:** setting up and aligning optical setup, understanding polarization and Stokes parameters, data analysis **Key References:** 

[1] Bhattacharya et al., Quantum dot polarized light sources, Semicond. Sci. Technol. 26 (2011) 014002

[2] Gerhardt & Hofmann, Adv Opt Tech 2012, 268949 (2012)

[3] Doogan et al., Evidence for spin memory

in photoluminescence of room temperature vertical-cavity quantum dot gain structure. Conference on Lasers and Electroptics - CLEO-Europe 2021. PD 1.1, 2021

Project Composition:	Theory: 5%	Computation: 15%	<b>Experimentation:</b> 80%

**Recommended Background or Pre-Requisites:** student should take PH445 Photonics and ideally PH453 solid state physics in sem 1. Student need to be willing to undertake potentially tedious optical alignment tasks.

Additional Safety Training required: Laser safety Suitable for: MPhys, BSc, BSc Maths and Physics Notes:

### Thermalization and Bose-Einstein condensation of photons in VCSELs

Project ID: TA3 Primary Supervisor: Thorsten Ackemann **Division:** Optics **Email:** thorsten.ackemann@strath.ac.uk

Secondary Supervisor: Thorsten Ackemann Secondary Supervisor(s): Konstantinos Lagoudakis

**Project Background:** The Bose-Einstein condensation of atoms constitutes a striking consequence of quantum statistics leading to the occupation of a macroscopic quantum state. Work focused on massive particles like cold atoms but quasi-particles can also condense. Photons are also bosons and acquire an effective mass in a microcavity. In [1] it was demonstrated that the interaction of photons in a dye-filled microcavity can lead to the thermalization of photons between transverse modes and a macroscopic occupation of the lowest order mode beyond a threshold interpreted as Bose-Einstein condensation of photons. Although there is still a discussion on the difference between BEC of photons and conventional lasing (e.g. [2]), the concept of photon BEC seems to be mainly accepted in the community by now. Very recently, thermalization of photons and potentially condensation [3] was reported in a semiconductor laser, a broad-area vertical-cavity surface-emitting lasers (VCSEL) [4]. The project will look experimentally into the transverse mode spectrum of VCSELs and collect evidence of thermalization and potentially condensation phenomena and its relation to lasing. Control parameters are device temperature and injection current.

Aim: We will look at the distribution of photons within the transverse modes of vertical-cavity surface emitting lasers and analyze their statistics with a few of demonstrating bosonic condensation phenomena.
 Tasks: Align optical setups. Measure Fourier spectrum of emitted light. Analyse via Python and (try to) fit to Bose-Einstein distributions

#### **Key References:**

[1] Jan Klaers, Julian Schmitt, Frank Vewinger & Martin Weitz, Bose–Einstein condensation of photons in an optical microcavity, Nature 468, 545 (2010)

[2] Julian Schmitt, Tobias Damm, David Dung, Frank Vewinger, Jan Klaers, and Martin Weitz, Thermalization kinetics of light: From laser dynamics to equilibrium condensation of photons. Phys. Rev. A 92, 011602 (2015)
[3] S. Barland et al., Opt. Exp. 29, 8368 (2021)

Project Composition:Theory: 15%Computation: 35%Experimentation: 50%

**Recommended Background or Pre-Requisites:** Python as taught in year 1-3, student should take PH445 Photonics and ideally PH453 solid state physics in sem 1.

Additional Safety Training required: laser safety awareness Suitable for: Mphys, BSc Notes:

### Quantum computing with quantum versions of random walks

#### Project ID: VK1

#### Division: Optics Email: viv.kendon@strath.ac.uk

Primary Supervisor: Viv Kendon

Secondary Supervisor(s): Rhonda Au Yeung, Steph Foulds

**Project Background:** Quantum versions of random walks have many diverse applications, for a review see [1], for applications to computation, see [2,3]. In this project, you will explore the behaviour of quantum walks in discrete or continuous-time evolution, and choose your applications from a wide range of options, depending on your interests and the current research projects we are engaged in. We are particularly interested in quantum computing applications [2,3], and applications to quantum transport. Note that [3] is a paper based partly on work done for this project in 2022-3. Quantum walks are easy to simulate numerically, and some cases are amenable to analytical solution. Quantum versions of random walks come in both discrete-time and continuous-time versions. We know that both can be used to do quantum computation. The simulations of quantum walks are straightforward with your current knowledge of Python (other programming languages are fine if you prefer). There is scope to develop your computational skills, it is also fine to take a more analytical approach and keep the numerical component simple (you'll at least want to produce some nice graphs, though). Continuous-time quantum walks can be solved analytically using Green's functions, and discrete-time walks using Fourier-space methods, provided there is enough symmetry in the particular problem being tackled.

**Aim:** Learn how quantum computing works using quantum versions of random walks, then develop applications. There is scope for testing using the free time available online on commercial quantum computers (this is the experimental component).

**Tasks:** Reproduce simple discrete time and continuous time quantum walks in one and two dimensions; apply the quantum walks to the quantum walk search algorithm in two and more dimensions; choose an application and develop a quantum walk algorithm to solve it; (optional) implement your quantum algorithm on one of the commercially available quantum computers. Other topics are possible within this framework, more options will be suggested during the first Semester.

#### **Key References:**

[1] Quantum walks: a comprehensive review, Salvador E. Venegas-Andraca, Quantum Information Processing vol. 11(5), pp. 1015-1106 (2012) https://arxiv.org/abs/1201.4780

[2] V Kendon, A random walk approach to quantum algorithms, Phil. Trans. R. Soc. A (2006) 364, 3407-3422 https://arxiv.org/abs/quant-ph/0609035

[3] Lasse Gerblich, Tamanna Dasanjh, Horatio Q. X. Wong, David Ross, Leonardo Novo, Nicholas Chancellor, Viv Kendon 2024 Advantages of multistage quantum walks over QAOA , https://arxiv.org/abs/2407.06663

Project Composition:	Theory: 0%	Computation: 0%	<b>Experimentation:</b> 0%

**Recommended Background or Pre-Requisites:** Any suitable programming language can be used (e.g., Python, Julia, Matlab, C/C++, Fortran ...) There is a trade off between programming and theory, less of one means more of the other.

#### Additional Safety Training required:

Suitable for: MPhys, BSc, BSc Maths and Physics

**Notes:** Several students can take this project; each will end up with a distinct different project within the overall topic.

### Chip-scale atomic metrology

Project ID: JM1

Primary Supervisor: James McGilligan Secondary Supervisor(s): Paul Griffin Division: Optics Email: james.mcgilligan@strath.ac.uk

**Project Background:** The separation of atomic energy levels provides a previously unobtainable accuracy and precision in metrology, with an SI traceable reference to frequency and wavelength. Instrumentation that utilise atomic spectroscopy for metrology remain at the state-of-the-art for atomic clocks, magnetometers and wavelength references. Recent advancements in micro-electro-mechanical-system (MEMS) vapour cells have supported the miniaturisation and commercialisation of atomic metrological instruments in millilitre packages. Here in the Experimental Quantum Optics and Photonics team we are developing new techniques for system miniaturisation that offer the potential to revolutionise the next generation of atomic based quantum technologies.

**Aim:** This project aims to construct a chip-scale wavelength reference using coherent population trapping in a micro-fabricated platform.

**Tasks:** This project will focus on the development of a chip-scale wavelength reference, utilising a microfabricated package for rubidium vapour spectroscopy. The project will involve hands on experimental measurements for next generation atomic sensors, covering topics in micro-fabrication, atomic metrology and quantum sensors. Specifically, the project aims to realise a narrow atomic transition for laser locking in a millilitre package using coherent population trapping and measurement of different vapour cell dimensions. The completion of this study will establish a well understood narrow wavelength reference for chip-scale metrological applications.

### **Key References:**

[1] John Kitching , "Chip-scale atomic devices", Applied Physics Reviews 5, 031302 (2018) https://doi.org/10.1063/1.5026238

[2] J. P. McGilligan et. al. "Invited Review: Micro-fabricated components for cold atom sensors "https://arxiv.org/abs/2208.00680

[3] S. Dyer, et. al. "Micro-machined deep silicon atomic vapor cells " https://arxiv.org/abs/2207.12904

Project Composition:	Theory: 15%	Computation: 15%	<b>Experimentation:</b> 70%
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**Recommended Background or Pre-Requisites:** The main criteria are that you are keen to work on experiments and as part of a team.

Additional Safety Training required: Standard safety training as part of EQOP group, including lasers and electronics Suitable for: MPhys, BSc, BSc Maths and Physics Notes:

# Nanoscience

### Radiofrequency circuits for spin qubit readout

Project ID: AR1

Primary Supervisor: Alessandro Rossi Secondary Supervisor(s): Kristopher Barr (PDRA) Division: Nanoscience Email: alessandro.rossi@strath.ac.uk

**Project Background:** Radiofrequency reflectometry is an experimental technique that can provide fast and sensitive electrical readout of spin qubits in semiconductor quantum dot devices coupled to resonant circuits at cryogenic temperature. To optimize readout sensitivity, in situ frequency tuning and impedance matching of the resonator circuit is desirable. This project will devise strategies to improve the readout by simulating and designing electronic circuits with components that can be tuned or selected/deselected in the cryogenic environment without the need for thermal cycling the samples. The student(s) will look into a variety of computational approaches which may result in using varactors and/or transistor switches.

**Aim:** Simulations of radiofrequency circuits and design of printed circuit boards to be used in cryogenic experiments for qubit readout.

**Tasks:** Simulations of different circuit designs with QUCS software. Design of printed circuit boards with KiCAD software. Experimental test of circuit frequency response with vector network analyser.

#### **Key References:**

[1] Chatterjee, A. et al., Semiconductor qubits in practice, Nature Rev.Phys. 3, 157 (2021)

[2] Vigneau, F. et al. Probing quantum devices with radio-frequency reflectometry. Appl. Phys. Rev. 10, 021305 (2023).

[3] Pozar, D. M. Microwave Engineering 4th edn (Wiley, 2012).

Project Composition:	<b>Theory:</b> 10%	Computation: 75%	Experimentation: 15%
rioject composition.	111COLY. 1070	computation. 7570	Experimentation. 1970

**Recommended Background or Pre-Requisites:** Electromagnetism, waves, electronic circuits, transmission line theory.

Additional Safety Training required: standard safety training applies Suitable for: any Notes: maximum 2 students

### Developing microscopy-based experiments for undergraduate teaching labs

#### Project ID: BP1

**Division:** Nanoscience **Email:** brian.patton@strath.ac.uk

Primary Supervisor: Brian Patton Secondary Supervisor(s): David McKee

**Project Background:** Many of the research groups within the Department of Physics use microscopy and imaging of sub-mm objects as key tools within their research. However, there aren't enough practicals that develop these skills within the 2nd and 3rd year undergraduate labs. This project will involve testing a commercial, off-the-shelf education kit provided by Thorlabs and adapting it for inclusion in future UG teaching lab curricula. The kit provides a full curriculum of experiments, however these may not fully mesh with the curriculum within the physics degree in Strathclyde. The student taking this project will be expected to target proposed experiments at an appropriate year group.

Aim: To test and adapt commercial optics teaching lab kit for use in undergraduate teaching labs.

**Tasks:** The student will set up and test the standard experiments supplied with the kit and then develop further upgrades that extend the learning potential of the equipment. They will also develop learning outcomes and draft lab notes, taking account of the abilities of the relevant target year grouping.

#### **Key References:**

[1] https://www.thorlabs.com/newgrouppage9.cfm?objectgroup\_id=11630#ad-image-0

[2] https://www.thepulsar.be/article/diy-camera-test-bench-setup

[3] https://www.thorlabs.com/newgrouppage9.cfm?objectgroup\_id=11829

Project Composition:	Theory: 20%	Computation: 10%	<b>Experimentation:</b> 70%
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Recommended Background or Pre-Requisites: Strong practical skills and interest in curriculum development

Additional Safety Training required: Laser safety training required Suitable for: N/A Notes: N/A

### Fabrication of low-cost and tuneable UV detectors

Project ID: FM1 Primary Supervisor: Fabien Massabuau Secondary Supervisor(s): Sean Douglas

Division: Nanoscience Email: f.massabuau@strath.ac.uk

**Project Background:** Gallium oxide (Ga2O3) is an emerging wide bandgap semiconductor (bandgap energy ~5eV) that finds applications in high power transistors, and ultraviolet detectors. Owing to its role in UV detection, Ga2O3 holds the key for a more sustainable future – in particular for ensuring access to clean water. However, the production of current Ga2O3 materials relies on expensive processes and multi-£M equipment. In order to ensure prompt development of the technology and ensure access to clear water for all, it is imperative to design low-cost routes to design this material.

Being a metal oxide, Ga2O3 can in principle be produced using chemical solution deposition, which presents the benefit of being much more versatile and cost-effective than conventional fabrication routes. However, that approach has been overlooked by the community, and the conditions leading to high-performing devices using that route are at the moment unexplored. The project aims to fill that gap of knowledge.

Aim: Synthesise and characterise Ga2O3 materials produced through chemical soution deposition **Tasks:** The student will (i) review the literature on chemical solution deposition of gallium oxide and related materials, (ii) produce Ga2O3-based films exploring a range of parameters, and (iii) characterise the films using scanning electron microscopy and UV-vis spectrophotometry. If time allows, (iv) we will process the films into UV detectors and test their characteristics.

#### **Key References:**

[1] Kokubun et al, Appl. Phys. Lett. 90, 031912 (2007) https://doi.org/10.1063/1.2432946

[2] Kokubun et al, Phys. Status Solidi A 207, 1741 (2010) https://doi.org/10.1002/pssa.200983712

[3] Chiang et al., Nanomaterials 12, 3601 (2022) https://doi.org/10.3390/nano12203601

Project Composition:	<b>Theory:</b> 10%	Computation: 30%	<b>Experimentation:</b> 60%
r oject composition.	110019. 1070	computation. 3070	Experimentation: 0070

**Recommended Background or Pre-Requisites:** The student must be comfortable with the content of the "Condensed Matter Physics" module (PH386). Attendance to "Topics on Solid State Physics" module (PH453) is strongly recommended.

Additional Safety Training required: Chemical safety training (COSHH) Suitable for: MPhys, BSc, BSc Maths and Physics Notes: The project is suitable for 2 students

### Luminescence properties of Ga2O3 semiconductors

#### Project ID: FM1

Division: Nanoscience Email: f.massabuau@strath.ac.uk

Primary Supervisor: Fabien Massabuau Secondary Supervisor(s): Rob Martin

**Project Background:** With a bandgap of ca. 5eV, gallium oxide (Ga2O3) is an ultra-wide bandgap semiconductor that finds applications in UV detectors as well as high power transistors. However, there is still a lot to discover about this material before it can be reliably used in devices. In particular, the nature and impact of defects in the crystal is still a point of debate and of technological importance.

Photoluminescence is a technique allowing to probe the electronic transitions of the material when excited using a light source (laser). Our group has recently built a new photoluminescence setup that should allow us to test the material under different conditions of temperature and power, which should enable us to build a more complete picture of the role of point defects on the electronic structure of Ga2O3.

Aim: Characterise the luminescence properties of new Ga2O3 semiconductors

**Tasks:** The student will (i) review the state-of-the-art in terms of luminescence of Ga2O3, (ii) acquire photoluminescence datasets of Ga2O3 samples containing different impurities, and (iii) analyse the dataset to identify the role of the impurities on the properties of Ga2O3.

#### **Key References:**

[1] McCluskey, J. Appl. Phys. 127 101101 (2020) https://doi.org/10.1063/1.5142195

[2] Zhang et al., APL Mater. 8, 020906 (2020) https://doi.org/10.1063/1.5142999

[3] Nicol et al., Appl. Phys. Lett. 122, 062102 (2023) https://doi.org/10.1063/5.0135103

Project Composition:	Theory: 20%	Computation: 20%	Experimentation: 60%
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**Recommended Background or Pre-Requisites:** The student must be comfortable with the content of the "Condensed Matter Physics" module (PH386). Attendance to "Topics on Solid State Physics" module (PH453) is strongly recommended.

Additional Safety Training required: Laser safety training Suitable for: MPhys, BSc, BSc Maths and Physics Notes: The project is suitable for 2 students

### Can wide bandgap semiconductors help us monitor better ocean health?

#### Project ID: FM2

#### Division: Nanoscience Email: f.massabuau@strath.ac.uk

Primary Supervisor: Fabien Massabuau Secondary Supervisor(s): David McKee

**Project Background:** The constituents of the water in our seas and oceans are important markers of the health of our planet. Being able to monitor how these constituents vary over time, or against specific events, will help us better understand the linkages that result in, for example, carbon capture in our bodies of waters. One approach to monitor water constituents is by doing so optically, that is, by measuring the absorbance of the medium at given wavelength. However, in-situ optical monitoring is challenging, and the few probes available commercially only use a restricted part of the light spectrum (ca. 350-800 nm). The recent emergence of wide bandgap semiconductors suitable for light emission and detection in the deep ultraviolet (ca. 250 nm) may provide exciting new opportunities to the field.

**Aim:** Evaluating the suitability of wide bandgap semiconductors to monitor the composition of sea water **Tasks:** The student will (i) conduct a literature review of the absorbance of seawaters, (ii) produce a set of samples mimicking seawater with different constituents, (iii) use UV-vis transmittance to survey the absorption of the samples in the deep UV, and (iv) use a photoconduction setup to test the suitability of a wide bandgap semiconductor detector for detection of the samples.

#### **Key References:**

[1] Ogura et al., Nature volume 212, 758 (1966) https://doi.org/10.1038/212758a0

[2] Dobbs et al., Water Research 6, 1173 (1972) https://doi.org/10.1016/0043-1354(72)90017-6

[3] Jonhson et al., Deep-SeaResearchI 49, 1291 (2002) https://doi.org/10.1016/S0967-0637(02)00020-1

Project Composition: Theory: 10% Computation: 30% Experimentation: 60%

**Recommended Background or Pre-Requisites:** 

Additional Safety Training required: Chemical safety training (COSHH) Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student only

### **Optical Microscopy Demonstrations**

Project ID: RM1 Primary Supervisor: Robert Martin Secondary Supervisor(s): Paul Edwards Division: Nanoscience Email: r.w.martin@strath.ac.uk

**Project Background:** The Optical Microscopy Course Kit contains components, documentation, and software for a full undergraduate course in optical microscopy. During the course, students build and operate a modular microscope in order to learn about image formation, resolution, aberrations, conjugate planes, and more. The course also introduces students to several imaging techniques such as darkfield, phase contrast, and fluorescence microscopy.

Extensive teaching materials are provided with this kit, including: Lab Notes, which guide students through procedures and exercises with the equipment; Course Notes, which detail the underlying scientific principles; and Instructor Notes, which provide useful tips for administering the course.

Aim: To build, test and evaluate a commercial kit for optical microscopy demonstations

**Tasks:** Work through a series of tasks in an Optical Microscopy coursebook: including Optical Imagin, Aberrations and Illumination, Kohler illumination, Contrast Methods for imaging, Fluorescence Microscopy **Key References:** 

[1] https://www.thorlabs.com/newgrouppage9.cfm?objectgroup\_id=11630#ad-image-0

[2] Reference links from ThorLabs (see link above)

[3] Undergraduate Optics Textbook e.g. "Optics" by Hecht

Project Composition: Theory: 10% Computation: 10% Experimentation: 80%

Recommended Background or Pre-Requisites: n/a

Additional Safety Training required: n/a Suitable for: all Notes: n/a

### Optical properties of plasmonic nanoparticles

Project ID: YC1

**Division:** Nanoscience **Email:** y.chen@strath.ac.uk

Primary Supervisor: Yu Chen Secondary Supervisor(s): Paul Edwards

**Project Background:** Gold nanoparticles exhibit significant potential across various scientific and technological fields due to their biocompatibility, accessibility, chemical versatility, and unique optical properties derived from surface plasmon resonance. This resonance allows the confinement of light at the nanoscale, leading to a localized enhancement of the electric field. Such plasmon-mediated concentration of the electric field around metallic nanostructures can amplify luminescence, facilitate energy transfer, and even trigger spasing processes, thereby opening avenues for innovation in areas ranging from biomedical applications to environmental sensing and advanced materials development.

**Aim:** This project aims to investigate the growth of asymmetric gold nanoparticles and examine the dependence of their optical properties on geometric shapes employing optical spectroscopy and scanning electron microscopy.

Tasks:

#### **Key References:**

[1] Eustis, S. and El-Sayed, MA. Why gold nanoparticles are more precious than pretty gold. Chem. Soc. Rev. 35, 209-217 (2006)

[2] Z. S. Mbalaha, P. R. Edwards, D. J. S. Birch and Y. Chen, ACS omega, 4, 13740-13746 (2019).

[3] M. Adelt, D. A. MacLaren, D. J.S. Birch and Y. Chen, ACS Applied Nano Materials. 4. 7730 (2021)

Project Composition:Theory: 50%Computation: 50%Experimentation: 90%

Recommended Background or Pre-Requisites: An interest in nanoscience and photonics

Additional Safety Training required: Chemical Handling, laser safety Suitable for: Notes:

### Plasmon enhanced fluorescence

Project ID: YC2

**Division:** Nanoscience **Email:** y.chen@strath.ac.uk

Primary Supervisor: Yu Chen Secondary Supervisor(s): Oliver Henrich

**Project Background:** Fluorescence spectroscopy and microscopy are powerful tools for non-invasive and nondestructive detection and visualization, capable of sensing and imaging at single molecule level. Despite the advantages, fluorescence technique is limited by weak emission from intrinsic fluorescence. Noble metal nanoparticles have unique optical properties dominated by localized surface plasmon effect. These plasmonic nanostructures are sensitive to local environment and can influence the optical process of adjacent molecules. As a result, they have broad applications ranging from chemical and biological sensing to light-harvesting enhancement in solar cells. Plasmonic nanostructures can enhance fluorescence emission via enhances excitation rate of a fluorescence emitter and changes the radiative and nonradiative decay rates. So far, a variety of plasmonic nanostructures has been developed to achieve fluorescence enhancement effect including metallic thin films, nanoparticles, ordered structures, waveguides and nanoantennas, resulting in increased brightness of molecular emission and improved detection sensitivity.

**Aim:** The aim of this project is to understand the influence of geometrical structure on enhancement factor **Tasks:** Study basic theory about fluorescence and fluorescence enhancement processes; literature search to review the development in metal enhanced fluorescence and its application; Study the influence of geometrical structure on the enhancement factor; analyze experimental data; writing report.

#### **Key References:**

[1] Li, J. et al. Plasmon-enhanced fluorescence spectroscopy, Chem. Soc. Rev. 46, 3962 (2017)

[2] Sun, S. et al. Critical role of shell in enhanced fluorescence of metal-dielectric core-shell nanoparticles, J. Phys. Chem. 124, 13365 (2020)

[3] Yu, H. et al. Plasmon-enhanced light-matter interactions and applications, NPJ Compu. Mat. 5, 45 (2019)

Project Composition:Theory: 20%Computation: 80%Experimentation: 0%

Recommended Background or Pre-Requisites: An interest in nanoscience and photonics

Additional Safety Training required: No special training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student

### Fluorescent noble metal quantum dots for nanomedicine

#### Project ID: YC3

**Division:** Nanoscience **Email:** y.chen@strath.ac.uk

Primary Supervisor: Yu Chen Secondary Supervisor(s): Oliver Henrich

**Project Background:** A fundamental understanding of the interactions between proteins and molecules is vital in developing diagnostics tool and therapeutics for numerous human diseases, including Alzheimer's, Parkinson's, Type II diabetes, cancer, and infectious diseases. Fluorescent protein-encapsulated noble metal nanoclusters (quantum dots) offer a non-toxic means of sensing and imaging biological phenomena on the nanoscale. They are highly stable, non-toxic, non-photobleaching, have extremely long fluorescent lifetimes, possess a large Stoke-shift and emit in the red-near IR regime. The latter minimises endogenous fluorescence, reduces Rayleigh scattering and permits work in the therapeutic window of tissue and cells.

**Aim:** This project aims to develop new sensing platforms based on peptide-encapsulated gold quantum dots. **Tasks:** We will investigate the fluorescence properties of noble metal quantum dots and develop NIR fluorescent nanoprobes.

#### Key References:

[1] Y. Peng, X. Huang and F. Wang, Chem. Commun., 57, 13012 (2021)

[2] B. A. Russell, K. Kubiak-Ossowska, P. A. Mulheran, D. J. S. Birch and Y. Chen, Phys. Chem. Chem. Phys., 17, 21935 (2015)

[3] A.M. Hada et. al, Microchim Acta, 189, 337 (2022)

Project Composition:Theory: 20%Computation: 80%Experimentation: 0%

**Recommended Background or Pre-Requisites:** 

Additional Safety Training required: Suitable for: Notes: One student

# Institute of Photonics

### Diode laser pumping of Ti:sapphire lasers

Project ID: AK1

Primary Supervisor: Alan Kemp Secondary Supervisor(s): Niall Simpson / Martin Lee **Division:** IOP **Email:** alan.kemp@strath.ac.uk

**Project Background:** High performance Ti:sapphire lasers are a workhorse laboratory tool across the photonic sciences, including important multi-disciplinary areas such as microscopy, spectroscopy, and quantum technology. This is a result of their excellent and adaptable performance characteristics. They are, however, bulky and expensive lasers, in large part because of the requirement to pump them with another relatively large and complex laser. This project will look at some of the practicalities and challenges of replacing the current pump lasers with inexpensive, but lower optical quality, diode lasers.

**Aim:** To assess how best to utilise inexpensive blue and green diode lasers for pumpng high performance Ti:sapphire lasers

**Tasks:** The project will attempt to reassess the pumping arrangements for Ti:sapphire lasers in the context of the availability of inexpensive blue and green diode lasers. Depending on progress of associated work in the team (https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/T014288/1), the project will involve some combination of characterisation of diode lasers, the design of optical systems for appropriately conditioning these diode lasers, calculations on the implications of diode laser pumping for Ti:sapphire laser performance, and the design of laser cavities suitable for diode laser pumping. The project would suit a student with an interest in photonics and, in particular, laser engineering, and will contribute to the work of a wider research group in this area. Ideally the student would be taking PH455 – the project will build significantly on the ideas introduced in this module.

#### **Key References:**

[1] P. W. Roth, A. J. Maclean, D. Burns, and A. J. Kemp, "Directly diode-laser-pumped Ti:sapphire laser," Optics Letters, vol. 34, pp. 3334-3336, 2009.

[2] J. C. E. Coyle, A. J. Kemp, J.-M. Hopkins, and A. A. Lagatsky, "Ultrafast diode-pumped Ti:sapphire laser with broad tunability," Optics Express, vol. 26, pp. 6826-6832, 2018

[3] H. Liu, S. Sun, L. Zheng, G. Wang, W. Tian, D. Zhang, H. Han, J. Zhu, and Z. Wei, "Review of laser-diode pumped Ti:sapphire laser," Microwave and Optical Technology Letters, vol. 63, pp. 2135-2144, 2021.

Project Composition:Theory: 0%Computation: 30%Experimentation: 70%

Recommended Background or Pre-Requisites: Student should normally be taking PH455 (Topics in Photonics).

Additional Safety Training required: Laser safety training must be be undertaken prior to any lab work. Suitable for: MPhys, BSc, BSc Maths and Physics Notes: Suitiable for up to 1 student.

### Laser Reflectometry in Plasma Etching System

#### Project ID: BG1

**Division:** IOP **Email:** benoit.guilhabert@strath.ac.uk

Primary Supervisor: Benoit Guilhabert Secondary Supervisor(s): Michael Strain

**Project Background:** Semiconductor device microfabrication relies on several key process steps; one of them is the plasma etching (dry etching) of the semiconductor layers, essential to form micron to the nano-scale pixels. To achieve optimum performances, exquisite control of the etched structure has to be achieved and end point measurement is utilised to achieve this by monitoring the etching process. It is based on the reflection intensity measurement of a laser beam incident on the semiconductor stack being etched [1]. The intensity variation over time is dependent on the refractive index and thickness of the materials forming the semiconductor stack while being etched away. The aim of the project is to model the reflection intensity in this process and provide analysis tool to infer parameters such as etching rate and material thicknesses [2-3]. A novel laser angled detection will also be investigated to employ a laser triangulation paradigm.

**Aim:** Model and test an end point paradigm to extract etching rates variation of epitaxial structures within a plasma etching (ICP) system

**Tasks:** 1 - Model a laser reflectometry by Transfer Matrix method in Maltlab or Python (student choice) at several laser wavelength and different incident angles

2 - With the model develop analysis tool to infer data from the etching process and the epitaxial structure

3 - Test the analysis tool developped on a real case: use of an end point detection on a cleanroom plasma etching tool (ICP) on a Gallium Nitride-based light-emitting diode structure

#### **Key References:**

[1] E.Teboul et al., An Optical Sensor for Real-Time In situ Endpoint Monitoring During Dry Etching of Multi-stack Layers, 48th Annual Technical Conference Proceedings, Society of Vacuum Coaters (2005)

[2] US6716362B1 - Method for thin film laser reflectance correlation for substrate etch endpoint

[3] US6905624B2 - Interferometric endpoint detection in a substrate etching process

Project Composition:	Theory: 15%	Computation: 55%	<b>Experimentation:</b> 30%

Recommended Background or Pre-Requisites: Matlab or Python

Additional Safety Training required: Safety induction to access the cleanroom laboratory

Introduction to plasma etching system use

Suitable for: Mphys, BSc, BSc Maths and Physics Notes: One student

# Vision-Based Motion Feedback Implementation for deterministic printing of semiconductor chiplets

#### Project ID: BG2

Primary Supervisor: Benoit Guilhabert

**Division:** IOP **Email:** benoit.guilhabert@strath.ac.uk

Secondary Supervisor(s): Sean Bommer

**Project Background:** Transfer Printing is a novel micro-fabrication technique that allows the heterogeneous integration of different semiconductor and insulator materials families together on a same platform by mechanical manipulation of micron- to nano-scale devices [1]. It employs a nanoscale accurate motion platform under a high-resolution optical microscope to displace devices in membrane format from their original substrate (Transfer) over to any receiving platform where they are released in place via Van der Waals interaction (Printing) [2]. Precise alignment is a requisite to achieve heterogeneous integration of devices such as ring resonators and nanowires onto photonic integrated circuits [3]. The aim of the project is to implement vision-based solutions to infer the accurate positioning of these devices onto receiver chips.

Aim: Implement Labview code for real-time camera acquisition and chiplet alignment within a Transfer Printing system

**Tasks:** 1 - Interface a CMOS camera within a LABVIEW interface following the code structure already established and implement acquisition options such as Region of Interest, pixel intensity over line profile

2 - Implement feature detections for the purpose of alignment functionalities such as centre of mass and crosscorrelation

3 - Test the code developped in the Transfer Printing system on real case: deterministic transfer of micron-size chiplets and alignment with the cleanroom laboratory

#### **Key References:**

[1] J. Yoon, et al., Advanced Optical Materials, vol. 3 (2015)

[2] J. McPhillimy et al., Optics. Express, vol. 26 (2018)

[3] J.A. Smith etal., Applied Physical Rview, vol. 9 (2022)

Project Composition:	<b>Theory:</b> 10%	Computation: 70%	Experimentation: 20%

Recommended Background or Pre-Requisites: LABVIEW

Additional Safety Training required: Safety induction to access the cleanroom laboratory Introduction to Transfer Printing technique and system Suitable for: Mphys, BSc, BSc Maths and Physics Notes: One student

### Automated characterisation of semiconductor nanowire devices

#### Project ID: DJ1

#### **Division:** IOP **Email:** dimitars.jevtics@strath.ac.uk

Primary Supervisor: Dimitars Jevtics Secondary Supervisor(s): Michael Strain

**Project Background:** In the last two decades, semiconductor nanowire emitters have attracted a significant attention due to their unique properties at the nanoscale: low-lasing threshold, high-optical confinement, and high-modulation bandwidths to name a few. These properties make nanowire devices attractive candidates as on-chip laser sources for photonic integrated circuitry (PIC). The ability to integrate these devices onto non-native substrates, into systems, or couple with waveguides, using heterogeneous pick-and-place techniques, has already showed promising results for next-generation PICs.

However, the nanowire-to-nanowire inhomogeneity driven by both structural and material properties prevents their further use in high-precision PIC and significantly reduces the fabrication yield, due to a drastic variation of their emission parameters. To overcome this challenge, large-scale characterisation of individual and clusters of nanowire emitters prior to their integration into systems, or with PICs is proposed.

For this class of devices, the characterisation is typically done using optical excitation techniques, using a lightemitting source, such as a laser. Using free-space optics, a laser source can be focused onto individual or groups of nanowire emitters which (if the right conditions are met) will then radiate light. The emitted light is then captured with a camera and spectrometer for further study and analysis. The automation of this process will enable sequential characterisation and positional registration of 1000s of devices. This non-destructive method will then allow to select individual or groups of nanowire devices with the desired emission parameters (threshold, wavelength), which in turn will enable the fabrication of high-precision PICs.

**Aim:** Development of an automated characterisation setup for quantitative measurements of semiconductor nanowire devices

**Tasks:** Training on free-space optics and micro-photoluminescence setup. Development of automated and computer-controlled measurements setup for characterisation of large arrays of semiconductor nanowire devices. Sample characterisation and analysis of large datasets to produce emission intensity maps and analysis of threshold points for various emitters.

#### **Key References:**

 J. A. Alanis et al., "Large-Scale Statistics for Threshold Optimization of Optically Pumped Nanowire Lasers," Nano Letters, vol. 17, no. 8. American Chemical Society (ACS), pp. 4860–4865, Jul. 25, 2017.
 D. Jevtics et al., "Characterization, Selection, and Microassembly of Nanowire Laser Systems," Nano Letters, vol. 20, no. 3. American Chemical Society (ACS), pp. 1862–1868, Feb. 04, 2020.
 [3]

Project Composition:	<b>Theory:</b> 10%	Computation: 35%	Experimentation: 55%
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**Recommended Background or Pre-Requisites:** A background in photonics, familiarity with basic lab equipment (lasers, spectrometers, optical fibres etc.), and basic programming skills (Python, C++) would be beneficial, but not expected.

Additional Safety Training required: Laser safety training Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student can take this project

### Optical chaos on a chip

#### Project ID: JPP1

Primary Supervisor: Javier Porte Parera

Secondary Supervisor(s): Michael J. Strain

Project Background: Dielectric microresonators are at the backbone of modern photonic integrated technologies.

Certain resonator geometries support aperiodic ray trajectories and can therefore exhibit optical chaos in absence of nonlinear effects.

A paradigmatic example of chaotic cavity is the Bunimovich stadium.

There, one expects no significant correlation in the trajectories of two light rays entering the cavity with slightly different initial conditions.

In consequence, when injected with a coherent light beam, the cavity's speckle pattern is highly sensitive to changes of phase from the input beam.

This complex behavior can be harnessed for photonic device applications in secret key generation and machine learning. In this project, the student will have the opportunity to investigate the generation of optical chaos in a stadium microresonator. The microresonators under study are fabricated in the clean room facility at the Institute of Photonics. The student will be involved in further discussions on the application of these resonators to on-chip photonic machine learning schemes.

Aim: Experimental characterization of optical chaos in a photonic integrated microresonator

Tasks: This project involves the alignment of an optical characterization setup to probe and measure photonic integrated circuits. Further, the student is expected to program the remote control of several laboratory instruments (e.g. signal generator, oscilloscope, and cameras) in order to automatize the measurement process. Finally, an offline analysis of the obtained data must be performed where the correlations between different microcavity's speckle patterns will be calculated.

#### **Key References:**

[1] H. Cao, and J. Wiersig, "Dielectric microcavities: Model systems for wave chaos and non-Hermitian physics", Rev. Mod. Phys., 87, 61-111 (2015).

[2] H. Cao, and Y. Eliezer, "Harnessing disorder for photonic device applications", Appl. Phys. Rev., 9, 011309 (2022)

[3] S. Sunada, and A. Uchida, "Photonic reservoir computing based on nonlinear wave dynamics at microscale", Sci. Rep., 9, 19078 (2019)

**Project Composition: Theory:** 10% **Computation:** 40% **Experimentation:** 50%

Recommended Background or Pre-Requisites: Background knowledge of Optics and Photonics is essential; General knowledge of scientific programming with Python or Matlab is recommended

Additional Safety Training required: Laser safety training required Suitable for: MPhys, BSc, BSc Maths and Physics Notes: One student can take this project

Division: IOP Email: javier.porte-parera@strath.ac.uk

### High-speed digital interfacing of Gallium Nitride light-emitting diodes

#### Project ID: JH1

# Division: IOP

Primary Supervisor: Johannes Herrnsdorf Secondary Supervisor(s): Jonathan McKendry Email: johannes.herrnsdorf@strath.ac.uk

**Project Background:** Light-emitting diodes (LEDs) based on III-Nitride semiconductor compounds have had revolutionary impact on lighting and displays by providing compact and efficient emitters of visible and ultraviolet light. Such LEDs are already being widely employed for energy-efficient lighting, displays, and water purification/sterilisation. Application areas of III-Nitride LEDs include wireless communications, remote sensing and ranging, fluorescence lifetime imaging, and Quantum Key Distribution, all of which require modulation of the LED brightness on a nanosecond timescale. A significant challenge in high-speed LED operation, especially at ultraviolet wavelengths, is the high operating voltage, which is typically in the regime 6-12 V. This is significantly higher than the ~3 V that is typical of infrared emitters. This project will explore approaches to achieve up to GHz modulation rates with such challenging voltage requirements.

**Aim:** To create and evaluate GHz-rate electronic control circuits to operate intensity-modulated light-emitting diodes with emission wavelengths in the visible and ultra-violet wavelength range.

**Tasks:** familiarisation with important characteristics of LEDs and device physics; familiarisation with field-effect transistor drivers for high-speed operation of LEDs; printed circuit board design; characterisation of optical output pulses (pulse duration, rise/fall times, pulse energy, repetition rate);

### **Key References:**

[1] MacLure et al., 10 Gbps wavelength division multiplexing using UV-A, UV-B, and UV-C micro-LEDs, Photonics Research 10, 516 (2022), https://doi.org/10.1364/PRJ.445984

[2] McKendry et al. Deep Ultraviolet CMOS-controlled Micro Light-Emitting Diode Array, IEEE Photonics Journal 15, 8200806 (2023), https://doi.org/10.1109/JPHOT.2023.3330571

[3] Xie et al., High-Speed Visible Light Communication Based on a III-Nitride Series-Biased Micro-LED Array, Journal of Lightwave technology 37, 1180 (2018), https://doi.org/10.1109/JLT.2018.2889380

Project Composition:Theory: 20%Computation: 10%Experimentation: 70%

Recommended Background or Pre-Requisites: Optics and Photonics

Additional Safety Training required: Laser safety training required, building access to TIC 507 required Suitable for: MPhys, BSc

Notes: Up to two students can take this project

### Comparing the attenuation lengths for µLED and laser sources in a brain phantom.

Project ID: NMc1 Primary Supervisor: Niall McAlinden Division: IOP Email: niall.mcalinden@strath.ac.uk

Secondary Supervisor(s): Keith Mathieson

**Project Background:** Optogenetics is a neuroscience technique that allows neuronal activity to be modulated by exposure to light. Getting light into the brain with the required intensity and spatial distribution is challenging, mainly due to the brains highly scattering nature. Most optogenetic light sensitive proteins are sensitive to blue light in the wavelength range from 440 nm to 480 nm which compounds the scattering issue. To mitigate some of the scattering issues several groups are working to develop orange/red (580-650nm) sensitive proteins. In this work, the student will test various light sources in a tissue phantom to quantify the improvements that can be achieved by using red sensitive optogenetic proteins. Experimental work will be compared to optical modelling. **Aim:** To compare the attenuation of  $\mu$ LED light and laser light of different wavelengths in scattering medium. **Tasks:** 1) Testing of  $\mu$ LED and Laser attenuation in water 2) Testing of  $\mu$ LED and Laser attenuation in scattering solutions (brian phantom) 3) Optical modelling of  $\mu$ LED and Laser attenuation in various medium. **Key References:** 

[1] https://www.nature.com/articles/s43586-022-00136-4

[2] https://onlinelibrary.wiley.com/doi/full/10.1002/advs.202105414

[3] https://ieeexplore.ieee.org/document/10413839

Project Composition:	<b>Theory:</b> 20%	Computation: 40%	Experimentation: 40%

Recommended Background or Pre-Requisites: An intererest in photonics

Additional Safety Training required: Laser safety will be required Suitable for: All Notes: One student can take this project.

### Effects of coherent optical feedback on class A SDLs

Project ID: PHM1

**Division:** IOP **Email:** jennifer.hastie@strath.ac.uk

Primary Supervisor: Paulo Hisao Moriya Secondary Supervisor(s): Prof Jennifer E. Hastie

**Project Background:** Robustness to coherent optical feedback is a desirable feature of high-performance lasers targeting quantum technologies (QT) applications, such as optical clocks, atom interferometers and photonic integrated circuits (PICs). It has a direct impact not only the laser dynamics, via the injection of excess noise which can lead to coherence collapse, but also its compactness, given extra components and stabilization might be required to protect the laser against optical feedback from the QT system. Optical isolators are the most common component used in optical systems but with limited availability in wavelength coverage especially at visible wavelengths. In this project, the robustness to optical feedback in VECSEL (vertical-external-cavity surface-emitting laser) technology will be investigated for the production of ultra-coherent, compact laser systems for QT applications.

**Aim:** Create a simple theoretical model and characterise the frequency/intensity noise performance of class A SDL under coherent optical feedback.

**Tasks:** Design of experimental setup for optical feedback measurements; Frequency stabilization of SDLs; Measurement of SDL frequency and intensity noise performance when subject to optical feedback; Data analysis; Adaptation of Petterman's model for SDLs.

#### **Key References:**

[1] J. Helms and K. Petermann, "A Simple Analytic-Expression for the Stable Operation Range of Laser-Diodes with Optical Feedback", J. Lightwave Technol. 9, 468 (1991).

[2] M. Guina et al., "Optically pumped VECSELs: review of technology and progress", J. Phys. D 50, 383001 (2017).
[3] P. H. Moriya et al., "Sub-kHz-linewidth VECSELs for cold atom experiments", Opt. Express 28, 15943 (2020).

Project Composition:Theory: 25%Computation: 25%Experimentation: 50%

**Recommended Background or Pre-Requisites:** Student should be comfortable with using Matlab, Python, or similar scientific programming language for developing simulations; Origin for plot and data analysis. Recommended modules PH462 Topics in Quantum Optics, PH455 Topics in Photonics.

Additional Safety Training required: Laser safety training is required.

Suitable for: MPhys, BSc, BSc Maths and Physics

Notes: The High Brightness Semiconductor Lasers team will accept one student for the 2024-25 academic year.

### Narrow linewidth monolithic InGaAs SDLs

Project ID: PMH2

**Division:** IOP **Email:** jennifer.hastie@strath.ac.uk

Primary Supervisor: Paulo Hisao Moriya Secondary Supervisor(s): Prof Jennifer E. Hastie

**Project Background:** The development of ultra-coherent light sources is key not only for the advancement of laser physics but also high precision applications, such as quantum technologies (QT). Few high-performance lasers with different brightness, wavelength emission and coherence levels are required to exploit the quantum nature of matter. Depending on the laser technology being used, external modules are required to achieve the required performance with direct impact in its compactness, stability and portability thus affecting the laser integration to QT systems. In this project, a single-frequency InGaAs-based monolithic cavity VECSEL (vertical-external-cavity surface-emitting lasers) system will be developed to investigate the laser noise performance when more compact frequency stabilisation references, such as micro-ring resonators, are used for the development of VECSEL systems with reduced bulkiness and complexity.

**Aim:** Development of compact, narrow linewidth InGaAs-based SDLs for quantum technology applications. **Tasks:** Design and construction of a monolothic cavity SDL; Optimization of brightness performance; Frequency and intensity noise reduction for single frequency operation; frequency stabilization of SDLs; SDL noise performance characterization.

#### **Key References:**

[1] P.H. Moriya et al., "Sub-kilohertz linewidth free-running monolithic cavity VECSEL with 10-12 stability", Appl. Phys. Lett. 125, 021101 (2024).

[2] M. Guina et al., "Optically pumped VECSELs: review of technology and progress", J. Phys. D 50, 383001 (2017).
[3] P. H. Moriya et al., "Sub-kHz-linewidth VECSELs for cold atom experiments", Opt. Express 28, 15943 (2020).

Project Composition:	<b>Theory:</b> 15%	Computation: 15%	<b>Experimentation:</b> 70%
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**Recommended Background or Pre-Requisites:** Student should be comfortable with using Matlab, Python, or similar scientific programming language for developing simulations; Origin for plot and data analysis . Recommended modules PH462 Topics in Quantum Optics, PH455 Topics in Photonics, PH459 Topics

Additional Safety Training required: Laser safety training is required.

Suitable for: MPhys, BSc, BSc Maths and Physics

Notes: The High Brightness Semiconductor Lasers team will accept one student for the 2024-25 academic year.

### Non-line-of-sight propagation model of Ultraviolet light

#### Project ID: SR1

**Division:** IoP **Email:** sujan.rajbhandari@strath.ac.uk

Primary Supervisor: Sujan Rajbhandari Secondary Supervisor(s): Dr Jonathan McKendry

**Project Background:** Optical wireless communication (OWC) technologies are highly appealing for the next generation of 5G and 6G telecommunications. The OWC offers an order of magnitude higher bandwidth than existing radio technologies. Among various wavelengths considered for OWC, deep ultraviolet wavelengths are particularly attractive for non-Line-of-Sight (nLOS) communication due to the high scattering probability by the atmosphere. The nLOS communication offers the advantage of alignment-free optical wireless communication offering high-mobility. The downside of the nLOS links is high path loss and limited channel bandwidth. **Aim:** Develop a non-line-of-sight channel model for UV propagation.

**Tasks:** Use the Monte Carlo method to Develop the nLOS channel model for UV light propagation for various light sources (Laser/LEDs) and receiver technologies, considering the divergence angle (of the light source), propagation distance and receiver field of view. Use the developed model to predict the received power, coverage and mobility for nLOS communication.

#### **Key References:**

[1] T. Cao, T. Wu, Changyong Pan, and J. Song, "Single-collision-induced path loss model of reflection-assisted non-line-of-sight ultraviolet communications," Opt. Express 30, 15227-15237, 2022

[2] H. Xiao, Y. Zuo, J. Wu, H. Guo, and J. Lin, "Non-line-of-sight ultraviolet single-scatter propagation model," Opt. Express 19, 17864-17875, 2011

[3] T. Cao, X. Gao, T. Wu, C. Pan and J. Song, "Reflection-Assisted Non-Line-of-Sight Ultraviolet Communications," in Journal of Lightwave Technology, 40 (7),1953-1961, 2022. AND Z. Ghassemlooy, W. O. Popoola, and S. Rajbhandari, Optical wireless communications – System and channel modelling with Matlab, 2nd ed. CRC Press, 2019

Project Composition: Theory: 20% Computation: 60% Experimentation: 20%

**Recommended Background or Pre-Requisites:** Students should be comfortable with using Matlab or similar scientific programming language (python) for developing simulations; background knowledge of Optics and Photonics is essential.

Additional Safety Training required: Laser safety training is required. Suitable for: MPhys, BSc, BSc Maths and Physics Notes: This project is open to one student.

## Study of imaging optical multiple-input-multiple-output (MIMO) free space optics in the

### presence of atmospheric turbulence

#### Project ID: SR2

Primary Supervisor: Sujan Rajbhandari

Division: IoP Email: sujan.rajbhandari@strath.ac.uk

Secondary Supervisor(s): Dr Jonathan McKendry

**Project Background:** Free-space optical communication (FSO) uses collimated light in the free space to enable wireless transmission of high-speed long-distance communication. One of the critical challenges for terrestrial long-distance FSO is atmospheric turbulence caused by variations in the temperature and pressure along the light propagation path. Various techniques, such as aperture averaging, adaptive optics, spatial diversity, etc., are applied to overcome the turbulence effect. The spatial diversities rely on the availability of uncorrelated independent channels to mitigate the turbulence effect at the receiver.

**Aim:** Develop an imaging optical multiple-input-multiple-output (MIMO) system with artificial intelligence to overcome atmospheric turbulence in FSO.

**Tasks:** Understand the atmosphere propagation of light and various turbulence models, understand the imaging optical multiple-input-multiple-output (MIMO) and develop an artificial intelligence-based algorithm to overcome the atmospheric turbulence for FSO.

#### **Key References:**

[1] N. Chimitt, S. H. Chan, "Simulating anisoplanatic turbulence by sampling intermodal and spatially correlated Zernike coefficients," Opt. Eng. 59(8) 083101 (3 August 2020)

 [2] L., Antonios, A. Sklavounos, A. Stassinakis, K. Cohn, A. Tsigopoulos, K. Peppas, K. Aidinis, and H. Nistazakis.
 2023. "Experimental Machine Learning Approach for Optical Turbulence and FSO Outage Performance Modeling" Electronics 12, no. 3: 506.

[3] Z. Ghassemlooy, W. O. Popoola, and S. Rajbhandari, Optical wireless communications – System and channel modelling with Matlab, 2nd ed. CRC Press, 2019.

Project Composition:Theory: 40%Computation: 60%Experimentation: 0%

**Recommended Background or Pre-Requisites:** Students should be comfortable using Matlab or similar scientific programming language to develop simulation platforms; background knowledge of Optics, Photonics and artificial intelligence is essential.

Additional Safety Training required: Laser safety training is required.

Suitable for: MPhys, BSc, BSc Maths and Physics

**Notes:** This project is open to one student.