Plasmas Division

Nonlinear waves in plasmas

(1) Dr Adam Noble, (2) Prof Dino Jaroszynski

Project Description:

One of the most noteworthy features of plasmas is the vast array of wave phenomena they can support. The properties of these waves will depend on the conditions of the plasma (density, temperature, magnetic fields...) as well as the polarisation of the wave and which component of the plasma (light electrons or heavy ions) is oscillating. Plasma waves are usually analysed in the linear limit, but as they are driven to higher amplitudes a rich suite of phenomena is unveiled.

This project will explore the range of waves that can propagate in plasma, and how nonlinear behaviour can lead to important effects such as wavebreaking, particle trapping and soliton-formation. It will also address the significance of these phenomena for ongoing endeavours to accelerate particles in plasma.

Key Reference:

Theory of Wave Motion of an Electron Plasma, AI Akhiezer and RV Polovin, Sov. Phys. JETP **3**, 696 (1956).

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	70%
Comp:	30%

Suitability: MPhys, BSc, BSc Maths and Physics

Additional comments: This project will suit mathematically minded students with an interest in widely applicable theoretical techniques. Anyone interested in pursuing this project should contact the supervisors beforehand.

Safety Training Requirements: None.

Simulation and measurement of two-dimensional periodic surface lattice

(1) Prof Adrian W. Cross, (2) Dr Craig W. Robertson

Project Description:

The main goal of the project is to study the interaction between two-dimensional (2D) periodic surface lattice (PSL) structures and electromagnetic waves. The primary objectives are: 1/ Theoretical study of electromagnetic wave propagation through a cylindrical 2D periodic surface lattice; 2/ Develop a CST Microwave Studio computer model of electromagnetic wave interaction with the 2D PSL; 3/ Experimental study of the transmission of electromagnetic radiation through the cylindrical 2D periodic surface lattice.

The properties of a periodic structure will be measured using a Vector Network Analyser. Experimental measurements will be compared with CST Microwave Studio simulations of the transmission of electromagnetic radiation through the structures**.**

Key Reference:

[1] I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, A.W. Cross and A.D.R. Phelps, 'Cylindrical periodic surface lattice as a metadielectric: Concept of a surface-field Cherenkov source of coherent radiation' Phys. Review A., **84**, art. 022902, 2011.

[2] I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, A.W. Cross and A.D.R. Phelps, "Cylindrical, periodic surface lattice-Theory, dispersion analysis, and experiment, Applied Physics Letters, **101**. 121111, 2012.

Ratio of effort: Exp/Theo/Comp

Exp:	20%
Theo:	30%
Comp:	50%

Suitability: PH550 M.Phys.

Additional comments:

Safety Training Requirements:

Design, simulation and experiments of an Extended Interaction Oscillator based on a pseudospark sourced sheet electron beam

(1) Prof Adrian W. Cross, (2) Dr Huabi Yin

Project Description:

A project is proposed to design, simulate, construct and measure the millimetre output radiation generated by a planar Extended Interaction Klystron Oscillator (EIKO) that uses a pseudospark-sourced sheet electron beam.

High frequency (365GHz) radiation sources are used in a number of diverse applications such as the study of the fundamental properties of materials, security and medical imaging, magnetic resonance spectroscopy and chemical sensing. The power that can be generated from 'bench top' free electron radiation sources in the hundreds of GHz to THz frequency range has been limited by the fact that as the frequency is increased, the size of the slow wave interaction region has to be reduced in order to prevent the maser becoming overmoded which results in a loss of the temporal or spatial coherence of the output radiation. As the frequency increases it becomes increasingly difficult (if not impossible) using conventional thermionic cathodes to focus and form high current density, high quality electron beams through the small size interaction region of the THz maser. A pseudospark plasma cathode can overcome current density limitations imposed by thermionic emission as well as being able to generate a sheet electron beam without the need to use an external magnetic field.

A pseudospark (PS) is an axially symmetric, self-sustained, transient, low pressure (typically 50-500 mTorr) gas discharge in a hollow cathode/planar anode configuration, which operates on the low pressure side of the hollow cathode analog to the Paschen curve. A useful property of this type of discharge is the formation of an electron beam during the breakdown process. During a PS discharge, low temperature plasma is formed as a copious source of electrons and can be regarded as a low work function surface that facilitates electron extraction. Because of the special geometry and discharge mechanism, the electron beam from a PS discharge can propagate without an external magnetic guiding field due to the existence of an ion-focusing channel. The ion-focusing channel is formed due to the background gas ionization by the front of the electron beam itself. For generation of high frequency radiation in millimetre wave and sub-millimetre wave region this beam is ideal due to its small beam size, compactness, long lifetime and ability to form sheet electron beams.

The project will involve the design, simulation and construction of a psuedospark-sourced sheet electron beam to power a planar Extended Interaction Klystron Oscillator (EIKO) which is extended in one direction as compared to conventional EIKOs based on a cylindrical electron beam. Millimetre wave radiation for the planar EIKO will be measured and compared to the results of analytical theory and numerical simulations.

Key Reference:

[1] S. E. Tsimring "Electron Beams and Microwave Vacuum Electronics", Wiley Series in Microwave and Optical Engineering, John Wiley and Sons Inc, ISBN-13-978-0-470-04816-0, (2007).

[2] H. Yin, A. W. Cross, W. He, A. D. R. Phelps, K. Ronald, D. Bowes, C.W. Roberson "Millimeter wave generation from a pseudospark-sourced electron beam". Phys. Plasmas 16 (2009).

[2] D. Bowes, H. Yin, W. He, A.W. Cross, K. Ronald, A.D.R. Phelps, D. Chen, P. Zhang, X. Chen and D. Li, "Visualization of a Pseudospark-Sourced Electron Beam", IEEE Transaction on Plasma Science, 42, 10, pp2826-2827, (2014).

Ratio of effort: Exp/Theo/Comp

Exp:	30%
Theo:	30%
Comp:	40%

Suitability: PH450 BSc and MPhys

Additional comments:

Safety Training Requirements: Part 1 and Part 2 of Safety Induction Course

Design, simulation and experiments of a microwave undulator

(1) Prof Adrian W. Cross, (2) Dr Liang Zhang

Project Description:

In a free electron laser (FEL) [1,2], the relativistic electron beam passes through a transverse periodic magnetic field to generate short-wavelength radiation. An undulator that is able to create such a magnetic field is important for FEL operation. In literature, the conventional permanent magnet undulators (PMUs) play a dominant role. The periodic magnetic field can also be generated by an electromagnetic wave. Such types of undulator are known as RF undulators or microwave undulators (MU), depending on the wavelength.

A microwave undulator (MU) that is an alternative to the permanent magnet undulators in a free electron laser (FEL) will be investigated. A microwave undulator cavity operating at ~37 GHz will be modelled using the 3D electromagnetic code CST microwave studio. The microwave undulator cavity will be designed and constructed with its properties measured using a Vector Network Analyser. The goal of the project will be to compare theory and simulation of the electromagnetic fields in the microwave undulator with measurement of electromagnetic wave propagation through the structure.

Key References:

[1] D. A. G. Deacon, L. R. Elias, J. M. J. Madey, G. J. Ramian, H. A. Schwettman, and T. I. Smith, "First Operation of a Free-Electron Laser," Phys. Rev. Lett., vol. 38, no. 16, pp. 892-894, April 1977. DOI: 10.1103/PhysRevLett.38.892

[2] Z. Huang and K.-J. Kim, "Review of x-ray free-electron laser theory," Physical Review Special Topics - Accelerators and Beams, vol. 10, no. 3, p. 034801, March 2007. DOI: 10.1103/PhysRevSTAB.10.034801

Ratio of effort: Exp/Theo/Comp

Exp:	30%
Theo:	30%
Comp:	40%

Suitability: BSc

Recommended Classes/Pre-requisites:

Additional comments:

Safety Training Requirements:

Beam-driven Plasma Wakefield Acceleration (PWFA)

(1) Prof Bernhard Hidding, (2) Prof Dino Jaroszynski

Project Description:

Electron beams can drive strong plasma waves which can sustain electric fields up to the Teravolt-per-meter scale. This is three or four orders of magnitude larger than state-of-the-art accelerators and may in turn allow to realize ultracompact high energy accelerators on the cm- instead of the km-scale. Particle beams are highly suitable for plasma acceleration, and this possibly transformative approach is mushrooming worldwide and has already spread to large labs such as CERN or SLAC. In addition to shrinking down the size of particle accelerators, at Strathclyde we have developed novel methods which are highly promising to also allow to increase the obtainable electron beam quality of plasma accelerators by orders of magnitude. In particular, the so called "Trojan Horse" plasma photocathode method [1-3] may allow to increase the electron beam brightness to orders of magnitude better than even those obtainable at the best state-of-the-art accelerators. Such an increase in beam quality is highly desirable for key applications such as for advanced light sources, e.g. undulator synchrotron sources [4] or even hard x-ray free-electron lasers.

Suitable intense electron beam drivers to excite the plasma wave in a process called plasma wakefield acceleration (PWFA) can be produced by large conventional accelerators such as at SLAC as well as by laser wakefield acceleration (LWFA). PWFA is a trending R&D field and will be studied in by means of particle-in-cell simulations, theory as well as in experiments in which the electron bunch output from laser-plasma-accelerators at Strathclyde and the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) will be used for the first time for PWFA.

Key References:

[1] Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-driven Plasma Blowout, B. Hidding et al., Physical Review Letters 108, 035001, 2012
[2] Single-stage plasma-based correlated energy spread compensation for ultrahigh 6D brightness electron beams, G.G. Manahan, F.A. Habib et al., Nature Communications 8, 15705 (2017)
[3] http://www.eupraxia-project.eu/the-brightest-electron-beams-of-the-world.html
[4] A compact synchrotron radiation source driven by a laser-plasma wakefield accelerator, H.P. Schlenvoigt et al., Nature Physics 4, 130-133 (2008)

Ratio of effort: Exp/Theo/Comp	Exp:	0-30%
	Theo:	20-50%
	Comp:	40-60%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: PH355 Physics Skills

Additional comments: This project is open to more than one student.

Safety Training Requirements: Laser and radiological safety training will be provided, if required.

Electron beam physics and transport modelling

(1) Prof Bernhard Hidding, (2) Dr Brian McNeil

Project Description:

Electron beams, either produced by conventional radiofrequency- or plasma-based accelerators, are fundamental drivers of scientific progress: electron accelerators are required for high energy physics as well as most advanced imaging devices such as free-electron lasers and other light sources, and many more applications in natural, material and life sciences [1]. Fundamental building blocks of accelerators are transport and beam conditioning elements which are typically based on ensembles of electromagnets or permanent magnets. Examples are magnetic chicanes e.g. for bunch compression, or quadrupole triplets for focusing of particle beams.

State-of-the-art accelerators push the boundaries of what is possible to generate in terms e.g. of electron beam current, emittance or brightness. In this project, transport and conditioning of intense electron beams will be explored and modelled. Theoretical fundamentals include topics such as Twiss parameters, Hill's equation, or phase space [2]. Computational tools such as elegant and SDDS [3] and/or Astra [4] will be used to describe and explore a transport beamline element. The student(s) will learn fundamental beam physics aspects and their computation, which is an indispensable part of any accelerator application. For example, beam transport elements for novel undulator-based light sources such as (hard) x-ray free-electron lasers will be calculated.

Key References:

[1] EuCARD – Applications of Accelerators, 2017 http://iiaglobal.com/wp-content/uploads/2017/07/EuCARD-Applications-of-Accelerators-2017.pdf
[2] Fundamentals of Beam Physics, J.B. Rosenzweig, Oxford University Press
[3] Overview of elegant and SDDS
http://www.aps.anl.gov/Accelerator_Systems_Division/Accelerator_Operations_Physics/elegant.html
[4] ASTRA http://www.desy.de/~mpyflo/

Ratio of effort: Exp/Theo/Comp

Exp:	0-30%
Theo:	20-50%
Comp:	50-80%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: PH355 Physics Skills

Additional comments: This project is open to more than one student.

Safety Training Requirements: None required.

Monte Carlo Modelling of Particle Beam-Matter Interaction

(1) Prof Bernhard Hidding, (2) Dr Mark Wiggins

Project Description:

Electron, proton and ion beams are important tools in the context of radiation damage and therapy in bio-systems, for space and aviation electronics or for shielding issues in context of nuclear reactors, fusion and particle accelerators in general. Various electromagnetic and nuclear processes are involved and will be explored and modelled. Key concepts are cross section, Mean Free Path, ionization track, Linear Energy Transfer, Bethe-Bloch equation, Bragg peak, scattering, straggling, bremsstrahlung, pair production etc. [1].

The Monte Carlo code Geant [2], which is a standard code in high-energy physics and related research incorporates all of the above mentioned (and many more) effects will be used to model the interaction of particle beams with matter. The tasks involve modelling of monoenergetic to broadband electron, proton and ion beams with finite divergence, interacting with slab/voxelized structures composed of different materials, extraction of deposited total ionizing and non-ionizing dose in a 3d volume, and implementation of more complex, realistic structures generated in CAD tools. This setup will then be used to understand and predict the depth-dose deposition and transmitted flux of various experimentally relevant setups. The project amalgamates various general key physics processes with the design of next generation accelerator applications for natural, material and life sciences.

Key References:

[1] Tavernier, S., Experimental Techniques in Nuclear and Particle Physics: Interaction of Particles in Matter, Springer, 2009

[2] Geant Monte Carlo Code http://geant4.cern.ch/

Ratio of effort: Exp/Theo/Comp		
	Exp:	0%
	Theo:	40-60%
	Comp:	40-60%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: PH355 Physics Skills

Additional comments: This project is open to more than one student.

Safety Training Requirements: None required.

Space Radiation Reproduction and Testing

(1) Prof Bernhard Hidding, (2) Dr Mark Wiggins

Project Description:

Space radiation is a great danger to electronics and astronauts onboard space vessels. The spectral flux of space electrons, protons and ions for example in the radiation belts (van-Allen belts) is inherently broadband, which is a feature hard to mimic with conventional radiation sources. Using laser-plasma-accelerators such as those developed at the Scottish Centre of the Application of Plasma-based Accelerators (SCAPA), however, has the potential to reproduce important kinds of space radiation exactly. Thus could have transformative impact for space exploration, because better testing may lead to better performance of space missions. Various effects of radiation in space such as spacecraft charging, single event effects etc. shall be explored and the suitability of laser-plasma-based particle radiation to generate such effects shall be analyzed. In particular, the effect of secondaries which may be generated upon incidence of high energy particles shall be analysed. This requires detailed knowledge of stopping power and reactions in the matter (both electronics as well as biological systems shall be regarded). Such secondaries are currently shifting in the focus of the radiation hardness assurance community. A proof-of-concept experiment shall be designed which is suitable to demonstrate such secondary production and its effect on space electronics or for radiobiology.

Key References:

[1] Laser-plasma-based Space Radiation Reproduction in the Laboratory, B. Hidding et al., *Scientific Reports* 7, 42354 (2017)
[2] http://www.bbc.co.uk/news/uk-scotland-39845085
[3] http://www.bbc.co.uk/news/av/uk-scotland-39876170/powerful-laser-to-make-space-exploration-safer
[4] http://physicsworld.com/cws/article/news/2017/may/12/space-radiation-brought-down-to-earth
[5] Strathclyde Centre for Doctoral Training PPALS http://ppals.phys.strath.ac.uk/
[6] http://radecs2017.com/Radecs2017/index.php
[7] http://www.nsrec.com/

Ratio of effort: Exp/Theo/Comp	Exp:	0-20%
	Theo:	20-50%
	Comp:	30-60%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: PH355 Physics Skills

Additional comments: This project is open to more than one student.

Safety Training Requirements: Laser and radiological safety training will be provided, if required.

Radiation reaction effects in ultra-intense laser-foil interactions

(1) Prof. Paul McKenna (2) Dr Remi Capdessus

Project Description:

Upcoming international laser facilities, such as the Extreme Light Infrastructure (ELI) and APOLLON will produce record laser intensities, in excess of 10^{23} Wcm^{-2}. When these ultra-intense laser pulses interact with thin metal foils, they ionize the target, producing a plasma. The ions within this plasma are subsequently accelerated to high energies. It is predicted that next-generation laser facilities will produce ions with energies of hundreds of MeVs, which have important applications in oncology and fast ignition fusion. At ultra-high intensities however, QED effects strongly influence the plasma dynamics and resulting ion beam properties. For example, electrons oscillating in the laser fields can acquire relativistic velocities, causing them to radiate away energy via synchrotron radiation. This energy loss can be interpreted in the classical framework as a recoil force acting on the electrons, known as the radiation reaction (RR) force.

Building on recent results on the effects of the RR force on plasma dynamics and radiation distribution during interactions with thin (50-500 nm) foils ([1], [2]), this project aims to investigate the effects of laser polarisation on the plasma energy partition and probe RR effects in the transition region between thin and thick foil ion acceleration mechanisms. This will involve running 1D and 2D Particle-In-Cell (PIC) code simulations and using Matlab to analyse the results, in order to investigate key aspects of the laser-plasma interaction. Whilst the project will be primarily simulation driven, there is the potential to develop an analytical model to describe any relevant simulation results.

Key References:

[1] Capdessus, R. and McKenna, P., 2015. Influence of radiation reaction force on ultra-intense laser-driven ion acceleration. *Physical Review E*, *91*(5), p.053105

[2] Duff, M.J., et al., 2018. Modelling the effects of the radiation reaction force on the interaction of thin foils with ultra-intense laser fields. *Plasma Physics and Controlled Fusion*, *60*(6), p.064006

[3] Tamburini, M., et al., 2010. Radiation reaction effects on radiation pressure acceleration. *New Journal of Physics*, *12*(12), p.123005

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	10%
	Comp:	90%

Suitability: BSc Physics, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites:

Additional comments:

Safety Training Requirements:

Plasma instabilities in intense laser-foil interactions

(1) Prof. Paul McKenna, (2) Dr. Martin King

Project description:

The interaction of an ultra-intense (>10^{20} W/cm^2) laser pulse with an ultrathin (nanometre scale) foil results in ionisation and the acceleration of high currents of energetic electrons and ions. Various types of instabilities can occur during the acceleration of these particles. Studies have shown that, for the thinnest targets, Rayleigh-Taylor-like instability develops at the laser plasma interface, and that plasma expansion of micron-thick targets is subject to the Weibel instability. Both of these processes result in filamentary structures in the electrostatic fields and thus are detrimental to laser-driven ion acceleration.

The proposed project will investigate the onset of instabilities in intense laser-foil interactions. It involves processing and analysing data from an experiment performed using the Gemini high power laser at the Central Laser Facility, STFC Rutherford Appleton Laboratory, Oxfordshire. The project will evolve to include simulating the onset of instabilities in laser-plasma interactions using a particle-in-cell code running on a high performance computer.

Key References:

[1] G. G. Scott *et al.*, "Diagnosis of Weibel instability evolution in the rear surface density scale lengths of laser solid interaction via proton acceleration" *New Journal of Physics*, 19, 043010 (2017).
[2] R. J. Gray *et al.*, "Laser pulse propagation and enhanced energy coupling to fast electrons in dense plasma gradients" *New Journal of Physics*, 16, 093027 (2014).
[3] B. Gonzalez-Izquierdo *et al.*, “Optically controlled dense current structures driven by relativistic plasma-aperture induced diffraction.” *Nature Physics*, 12, 505-512 (2016)

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	10%
	Comp:	90%

Suitability: BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites:

Additional comments:

Safety Training Requirements:

Laser-driven ion acceleration from ultrathin foils undergoing relativistic self-induced transparency

(1) Prof. Paul McKenna, (2) Dr. Robbie Wilson

Project Description:

The potential to produce compact sources of energetic (hundreds of MeV/nucleon) ions with unique beam properties, including short temporal duration, motivates an intense international research activity in high power laser-driven ion acceleration. These enabling sources are being applied for radiographic density diagnosis with micron-scale resolution, for probing highly transient electric and magnetic fields in plasmas with picosecond resolution, for the isochoric heating of matter and for probing radiation-induced processes in matter. Societal applications, such as in biomedicine (for example hadron therapy) and fusion energy have also been proposed. Some of the applications require higher ion energies than presently achieved, and many require high laser-to-ion energy conversion efficiency, as well as spectral and beam divergence control.

Efforts to increase the maximum ion energy have largely focused on the development of novel acceleration mechanisms involving ultrathin (tens-to-hundreds of nanometres) foil targets. The proposed project aims to characterise the spatial-intensity and energy distributions of beams of high energy protons accelerated during intense laser pulse interactions with ultrathin foils undergoing relativistic self-induced transparency. It involves processing and analysing data from an experiment performed earlier this year using the PHELIX high power laser facility at GSI in Darmstadt, Germany. The project may evolve to include simulating laser-driven ion acceleration using a particle-in-cell code.

Key References:

[1] A. Higginson *et al*., Near-100 MeV protons via a laser-driven transparency-enhanced hybrid acceleration scheme. Nature Communications, 9, 724 (2018)

[1] H. Padda, *et al*., "Intra-pulse transition between ion acceleration mechanisms in intense laser-foil interactions." Physics of Plasma, 23, 063116 (2016).

[2] H.W. Powell, et al., "Proton acceleration enhanced by a plasma jet in expanding foils undergoing relativistic transparency." New Joural of Physics, 17, 103033 (2015).

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	10%
	Comp:	90%

Suitability: BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites:

Additional comments:

Safety Training Requirements:

Medical Radioisotope Production using a Laser-Plasma Wakefield Accelerator

(1) Dr Mark Wiggins, (2) Prof Dino Jaroszynski

Project Description:

Laser-plasma wakefield accelerators (LWFAs) are very compact laser-driven accelerators that have the potential to replace conventional accelerators in many applications. Reactors are usually used to produce medical radioisotopes (primarily Tc-99m), but their imminent decommissioning is threatening a world-wide shortage. Cyclotrons can be used but these are expensive. This project will explore how a LWFA can be used to produce radioisotopes for diagnostic imaging such as positron emission tomography (PET) or for in vivo targeted radiation therapy (alpha or beta particle emitters).

These applications cover a wide variety of biologically important isotopes such as C-11, O-15, F-18, Cu-64, Tc-99m and Ac-225 and the flexibility of the LWFA lends itself to be a potential source of many useful isotopes. Proof-of-principle studies are underway to demonstrate the LWFA as a viable driver for medical radioisotope production. A monoenergetic, high energy electron beam from a LWFA is used to produce gamma rays via bremsstrahlung from the electron beam as it interacts with a metallic converter. The gamma rays then interact with a secondary target to produce the desired radioisotope via photonuclear reactions.

This project involves the use of a Monte Carlo simulation code to model the nuclear reaction processes for a variety of the radioisotope scenarios with a view towards optimising the experimental setup. Favourable scaling towards single patient doses for future high repetition rate LWFAs will also be explored.

Key References:

[1] "Developments in laser-driven plasma accelerators", S. M. Hooker, Nature Photon. **7**, 775 (2013).
[2] "Nuclear physics in particle therapy: a review", M. Durante and H. Paganetti, Rep. Prog. Phys. **79**, 096702 (2016).

Ratio of effort: Exp/Theo/Comp		
	Exp:	0%
	Theo:	20%
	Comp:	80%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: PH452 Topics in Physics, PH459 Topics In Atomic, Molecular And Nuclear Physics

Safety Training Requirements: none

Excitation of Heavy Atomic Species for ITER

(1) Prof Nigel Badnell, (2) TBC

Project Description:

The development of the ITER device for magnetic fusion requires the use of much heavier elements (Kr, Xe, W etc) than have traditionally been used, such as at the JET device.

Consequently, spectroscopic diagnostic modelling at ITER, which is already being simulated, requires atomic data where relativistic effects are likely much larger than have been seen before. The goal of the project is to assess the degree of importance of relativistic effects of relevance to ITER diagnostics. This will entail computational calculations of atomic data with varying degrees of treatments of relativistic effects viz. non-relativistic vs relativistic wavefunctions, the importance of the Breit interaction and the validity of its Pauli approximation at `low'-charge.

Key Reference: *http://www.iter.org/*

Ratio of Experiment/Theory/Computation:

Exp:	0 %
Theo:	30 %
Comp:	70 %

Suitable for: MPhys

Additional Comments: *Familiarity with Unix (e.g. Linux) working environment and good computing skills in general.*

Safety Training Requirements:

Atomic Processes for Astrophysical Plasmas

(1) Prof Nigel Badnell, (2) TBC

Project Description:

Collisions of electrons and photons with atoms, ions and molecules play a fundamental role in unfolding our understanding of the origin and evolution of the Universe. Knowledge of atomic collision processes permits investigations of past and present states of galaxies, gas clouds, stars and other objects via spectroscopy. In particular, the state of matter in each object the distribution of temperature and density, chemical composition, flow velocities, and the like may be determined. This kind of information is deduced from the spectra of the objects through diagnostic analysis in which models incorporating the full physics of the object confront the observations. It is these models which we seek to support.

In recent years, a wealth of XUV satellite spectra of solar (SOHO, Hinode/EIS, STEREO, SDO) and astrophysical (Chandra, XMMNewton, HST, FUSE) plasmas of the most varied sources (e.g. the solar corona, stellar atmospheres, supernova remnants, AGN, comets) have shown the richness in spectral lines and the potential for plasma diagnostics.

The project aim is to support atomic physics calculations needed to keep pace with observational capability, in order to enhance the scientific returns from these costly missions.

http://www.apapnetwork.org/

Key Reference: *Foster et al "The Challenges of Plasma Modeling: Current Status and Future Plans" Space Sci. Rev. v157 13554 (2010) http://link.springer.com/article/10.1007/s1121401097321*

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	30%
	Comp:	70%

Suitability: MPhys, BSc, BSc (Maths Physics)

Additional comments: *Familiarity with Unix (e.g. Linux) working environment and computing skills will be helpful.*

Safety Training Requirements: *N/A*

Stochastic Particle Heating of Charged Particles by Plasma Waves

(1) Dr Bengt Eliasson, (2) Dr Kevin Ronald

Project Description:

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 electromagnetic 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.

The project involves at building a numerical model for stochastic heating of charged particles (electrons and/or ions) in magnetized plasmas by using test-particle simulations, and to use the numerical model to study some different cases where stochastic heating takes place. A theoretical derivation and understanding of the mathematical models is also part of the project.

Key Reference: *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.*

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	50%
Comp:	50%

Suitability: MPhys, BSc, BSc Maths and Physics

Additional comments: *Experience in simulations using Matlab (or any other programming language) and good theoretical skills are beneficial.*

Safety Training Requirements:

Scattering of Relativistic Electrons off Electromagnetic Ion Cyclotron Waves

(1) Dr Bengt Eliasson, (2) Dr Kevin Ronald

Project Description:

Relativistic electrons with energies in the MeV range and protons in the 100 MeV range are mirror trapped in dipole field of the Earth in the van Allen radiation belts. The trapping is due to the conserved magnetic moment of the charged particles. High-energy particles are detrimental to the electronics on board spacecraft and satellites, and there is an effort to find ways to clean the radiation belts of relativistic electrons and ions by perturbing the gyro-motion of the particles so that they fall within a loss-cone and are absorbed by the neutral gas of the lower ionosphere. Obeying a certain resonance condition the particles can interact with the electromagnetic waves leading to pitch angle scattering into the loss cone. Low frequency electromagnetic waves occur naturally due to solar storms, and are also produced due to man-made transmitters. Laboratory experiments have also been carried out to study pitch-angle scattering of mirror-contained particles by low-frequency electromagnetic waves. The project involves carrying out test-particle simulations to study the scattering of relativistic electrons by electromagnetic ion cyclotron waves near the ion cyclotron resonance in a diverging magnetic field, and comparing the results with theoretical expressions of pitch angle diffusion. The programming language is likely to be Matlab or similar high level language.

Key References:

[1] B. Eliasson and K. Papadopoulos: Pitch angle scattering of relativistic electrons near EMIC resonances in diverging magnetic fields. Plasma Physics and Controlled Fusion **59**(10), 104003, doi:10.1088/1361-6587/aa8100 (2017).
[2] Summers, D., and R. M. Thorne (2003), Relativistic electron pitch-angle scattering by electromagnetic ion cyclotron waves during geomagnetic storms, *J. Geophys. Res.*, 108, 1143, doi:10.1029/2002JA009489, A4.
[3] Van Compernolle B, Bortnik J, Pribyl P, Gekelman W, Nakamoto M, Tao X and Thorne R M 2014 Direct detection of resonant electron pitch angle scattering by whistler waves in a laboratory plasma Phys. Rev. Lett. 112 145006
[4] Vincena S, Gekelman W and Maggs J 2001 Shear Alfvén waves in a magnetic beach and the roles of electron and ion damping Phys. Plasmas 8 3884–96
[5] Öztürk M K 2016 Trajectories of charged particles trapped in Earth's magnetic field Am. J. Phys. 80 420–8
[6] Stix T H 1960 Absorption of plasma waves Phys. Fluids 3 19–32

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	40%
Comp:	60%

Suitability: MSc in Applied/Advanced Physics

Recommended Classes/Pre-requisites: PH355 Physics Skills, PH352, EM and Quantum Physics, PH452 and PH560 Plasma Physics, good theoretical and numerical skills.

Safety Training Requirements: Induction TIC building, use of computer workstations.

Design of a Frequency Swept, Multi-Megawatt, Cherenkov Oscillator

(1) Dr Philip MacInnes, (2) Dr Kevin Ronald

Project Description:

The aim of the proposed project is to design a frequency-tuneable high-power microwave oscillator; specifically a Relativistic Backward-Wave Oscillator (RBWO).

There are a number of novel challenges associated with sources of this type, for example the design of the charged particle accelerator that provides the input electron beam, or the design of the interaction region that couples energy from said beam into a growing EM field. The project therefore offers a range of different aspects for investigation, with the focus of the project decided through discussion with the student early on in the project.

Over the course of the project the student will have the opportunity to gain experience working with a variety of numerical simulation packages, as appropriate to different stages in microwave source design. They will also have the opportunity to develop skills working with MATLAB (potentially also PYTHON) in post-processing and analysis of results.

Key References:

H.R. Johnson Proc. Of the IRE, 43(6), 1955, pp. 684-697

V.L. Bratman et. al, Phys. Plasmas, 17(11), 2010, article: 110703

J.A. Swegle et. al, Phys. Fluids, 28(9), 1985, pp. 2882 - 2894

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	20-30%
	Comp:	70-80%

Suitability: MPhys, BSc Maths and Physics,

Recommended Classes/Pre-requisites: PH254 – computational Physics PH352 – Quantum Physics and Electromagnetism PH452 – Topics in Physics

Additional comments: Experience with MATLAB and / or equivalent high-level programming language(s) strongly recommended

Safety Training Requirements: None.

Design of a Brewster Window for a W-band Gyro-TWA

(1) Dr Wenlong He, (2) Dr Liang Zhang

Project Description:

A W-band gyrotron-travelling wave amplifier (gyro-TWA) based on a helically corrugated waveguide and a cusp electron gun is currently being studied. It is predicted to achieve an output power of 5 kW over a wide frequency band of 90 - 100 GHz. For an amplifier the microwave window, which separates the high vacuum side from the atmospheric pressure outside must couple in or out the microwave power with minimum absorption or reflection, and is one of the critical components for the successful operation of the gyro-TWA.

In this project, a Brewster-type microwave window will be studied using analytical theory. Numerical simulations Brewster-type microwave window will be carried out using CST Microwave Studio. A corrugated waveguide that maintains the Gaussian-like HE mode required for the Brewster window will also be designed and simulated. The design goals of the Brewster window are 10% bandwidth at a centre frequency of 95 GHz, small insertion loss and a reflection of less than -20 dB for the operating band. If the design meets the requirement, the Brewster window will be manufactured and measured using a Vector Network Analyser (VNA).

Key References:

[1] Wenlong He, Craig R. Donaldson, Liang Zhang, Kevin Ronald, Paul McElhinney and Adrian W. Cross, "High Power Wideband Gyrotron Backward Wave Oscillator Operating towards the Terahertz Region", Physical Review Letters, 110(16):165101, 04, 2013.

[2] Paul McElhinney, Craig R. Donaldson, Liang Zhang and Wenlong He, "A High Directivity Broadband Corrugated Horn for W-band Gyro-devices", IEEE Transactions on Antennas and Propagation, vol. 61, no. 3, pp. 1453-1456, 2013.

Ratio of effort: Exp/Theo/Comp	Exp:	20%
	Theo:	30%
	Comp:	50%

Suitability: MPhys, BSc, BSc Maths and Physics

Additional comments:

Safety Training Requirements: *High voltages will* ***<u>not</u>*** *be used and X-ray emission will* ***<u>not</u>*** *be generated during this project although a risk assessment will need to be completed in semester 1.*

Design and Measurement of a Mode Converter for a Microwave Amplifier

(1) Dr Wenlong He, (2) Dr Craig Donaldson

Project Description:

A microwave amplifier in the form of a gyrotron traveling wave amplifier is being studied at the University of Strathclyde. The amplifier uses the interaction between a rotating electron beam and a low power microwave signal to amplify the microwaves to high power over a wide bandwidth. In order to have the correct interaction a low power microwave signal needs to go through a mode converter to change from a $TE_{1,1}$ mode to a $TE_{3,1}$ mode.

In this project, a mode converter will be studied using analytical theory. Numerical simulations will be carried out using CST Microwave Studio. This converter is a four-fold helical corrugated waveguide. Initially this will be studied and measured using a vector network analyser (VNA), at X-band frequencies ~9 GHz.

In year 2 of the project the converter will be scaled down in size to operate at a much higher frequency in the W-band, at ~ 94 GHz. In both applications the converter will have to operate over the amplifiers bandwidth range of 10GHz and have a high conversion efficiency whilst maintaining a low reflection coefficient.

Key Reference: *He W., Donaldson C.R, Zhang L., Ronald K., McElhinney P., and Cross A.W., "High power wideband gyrotron backward wave oscillator towards the terahertz region", Phys. Rev. Letts, 110, art 165101, (2013).*

Ratio of effort: Exp/Theo/Comp	Exp:	25%
	Theo:	25%
	Comp:	50%

Suitability: MPhys

Additional comments:

Safety Training Requirements: *High voltages and X-ray emission will **not** be required for this project although a risk assessment will need to be completed in semester 1.*

Simulations of the Demonstration of Ionisation Cooling Experiment

(1) Dr Alan Young, (2) Dr Kevin Ronald

Project Description:

Due to their greater mass than electrons (approximately 200 times greater) and their decay mechanism, muons are very appealing for the study of fundamental particle physics, either through a muon collider or a neutrino factory. An important step in realising this potential are the development of techniques to improve the quality of muon beams and ionisation cooling has been identified as an attractive method for achieving this. Ionisation cooling uses the interaction of the muons with low Z absorbers to reduce the momentum spread while RF cavities are used to maintain the energy. Such a mechanism is very rapid, this is critical as with a mean lifetime of 2.2µs it is essential that the muons are rapidly cooled and accelerated to relativistic velocities to extend their lifetime. The international Muon Ionisation Cooling Experiment (MICE) aims to demonstrate this effect for the first time. Current models of the MICE experiment have assumed certain levels of RF gradient and field structure in the cavities. This project will aim to test the sensitivity of ionisation cooling to these parameters.

Key Reference: *Adams D. et al, 2013, 'Characterisation of the muon beams for the Muon Ionisation Cooling Experiment' Euro. Phys. J. C,* ***73,*** *art. 2582*

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	20%
	Comp:	80%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Additional comments:

Safety Training Requirements:

Nonlinear Vacuum Electrodynamics

(1) Dr Adam Noble, (2) Prof Dino Jaroszynski, Dr Samuel Yoffe

Project Description:

An important characteristic of Maxwell's equations in vacuum is that they are linear. In certain material media, by contrast, interactions with the particles comprising the medium can induce nonlinearities. Due to the presence of virtual electron-positron pairs, the quantum vacuum can itself behave like an exotic medium, in which nonlinear interactions can modify the propagation of light. Similar phenomena are predicted in the low energy limit of more speculative branches of physics, such as string theory.

This project will explore some of the consequences of nonlinear vacuum theories of electrodynamics, such as the refractive index of strong electric and magnetic fields, birefringence, and light-by-light scattering. Prospects for detecting such phenomena at upcoming laser facilities will also be considered.

Key Reference:

Limits on nonlinear electrodynamics, M Fouché, R Battesti and C Rizzo, Phys. Rev. D **93**, 093020 (2016).

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	At least 70%
	Comp:	Up to 30%

Suitability: MPhys, BSc, BSc Maths and Physics

Additional comments: This challenging project will suit an ambitious student with strong mathematical skills, who enjoys exploring technical and conceptual questions. Anyone interested in pursuing this project should contact the supervisors beforehand.

Radiation Reaction

(1) Dr Adam Noble, (2) Prof Dino Jaroszynski, Dr Samuel Yoffe

Project Description:

The nature of electromagnetic radiation reaction – how an electron interacts with the radiation it emits – is one of the oldest open questions in physics. The "standard" description exhibits unphysical behaviour (self-acceleration, violation of causality), and proposed alternatives remain contentious. With the advent of a new generation of laser facilities operating at unprecedented intensities, it is more important than ever to properly understand radiation reaction.

This project will explore the difficulties involved in the theoretical description of radiation reaction, and some of the attempts to overcome them. It will also investigate how additional effects, for example due to spin and quantum mechanics, might affect radiation reaction in the context of high-power lasers.

Key References:

Aspects of electromagnetic radiation reaction in strong fields, DA Burton and A Noble, Contemp. Phys. **55**, 110 (2014).

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	At least 50%
Comp:	Up to 50%

Suitability: MPhys, BSc, BSc Maths and Physics

Additional comments: This challenging project will suit an ambitious student with strong mathematical skills, who enjoys exploring technical and conceptual questions. Anyone interested in pursuing this project should contact the supervisors beforehand.

Ion Channel Laser with Large Oscillation Amplitude

(1) Dr Bernhard Ersfeld, (2) Prof Dino Jaroszynski

Project Description:

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). As an important difference, an efficient ICL requires oscillation amplitudes in excess of the electron beam width, which reduces the overlap with the emitted radiation.

The project offers the opportunity to investigate, analytically and numerically, effects of such large oscillation amplitudes, like harmonic generation and correlations between longitudinal and transverse electron motion.

Key References: B. Ersfeld et al., "The ion channel free-electron laser with varying betatron amplitude", New Journal of Physics **16** (9), 093025 (2014), and literature on free-electron lasers

Ratio of effort: Exp/Theo/Comp

Exp:	0 %
Theo:	50 %
Comp:	50 %

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

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

Additional comments: Anyone interested in taking up this project should contact the supervisors beforehand.

Safety Training Requirements: None

An ultrafast, time-resolving ion spectrometer as a diagnostic of intense laser-plasma dynamics

(1) Dr Ross Gray (2) Dr Robbie Wilson

Project Description:

By focusing petawatt-scale pulses of laser light to intensities exceeding 10^{18} W/cm^2 matter is rapidly ionised and heated to temperatures in excess of >10^9 K on timescales of 10's of femtoseconds. Under these conditions the resulting plasma evolves into an exotic state of matter called a *relativistic plasma*, as electrons are accelerated to velocities approaching the speed of light. These electrons set up exceptionally strong (TV/m) electric fields which then act to accelerate the ions in the plasma to high energies over distances significantly shorter than conventional particle accelerators. In recent years there has been a great deal of interest in developing these new ions sources for applications including cancer therapy and nuclear fusion [1].

A key challenge, which arises due to the very short duration of the interaction, is in understanding and making measurements of the temporal dynamics of the interaction and the resulting ion beam. In this project we will aim to design and develop a new type of ultrafast time and energy resolving spectrometer based on a Thomson parabola spectrometer [2] which will open up new understanding of the ion acceleration and plasma dynamics.

This project will primarily focus on the design and development of this new diagnostic through the implementation of custom physics models. We will primarily make use of MATLAB, the EPOCH plasma simulation code as well as some design work in AutoCAD.

Key References:

[1] H. Daido *et al.*, Rep. Prog. Phys. **75** 056401 (2012)
[2] A. Alejo *et al.,* J. Inst **11**, C10005 (2016)

Ratio of effort: Exp/Theo/Comp

Exp:	10%
Theo:	20%
Comp:	70%

Suitability: BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH452 Topics in Physics (Recommended but not required)

Additional comments:

Safety Training Requirements: none

Plasma optical modulators for intense lasers

(1) Prof Zhengming Sheng, (2) Dr Feiyu Li

Project Description:

Optical modulators are key components for manipulating optical signals, which are widely used in scientific and industrial applications. For example, high-speed compact electro-optic modulators (EOMs) are essential for data communications. EOMs can alter the fundamental characteristics (that is, amplitude, frequency, phase and polarization) of a light beam in a controllable manner, by making use of electro-optic effects to change the refractive index of a material when an external radio-frequency electric field driver is applied. Normal EOMS can only apply for low light intensity due to the low optical damage threshold. Recently, we have proposed a plasma-based optical modulator [1], which can directly modulate high power lasers with intensity to produce an extremely broad spectrum with ultra-broad bandwidth.

The main task of this project is to investigate the effect of plasma density inhomogeneity along the laser propagation on frequency modulation. The student may also explore the effect of a plasma channel on frequency modulation to see the modulation limit. The student will use a one-dimensional and/or two-dimensional particle-in-cell (PIC) code to study this problem.

Key References:

[1] L.L. Yu, Y. Zhao, L.J. Qian, M. Chen, S.M. Weng, Z.M. Sheng, D.A. Jaroszynski, W.B. Mori, and J. Zhang, "Plasma optical modulators for intense lasers", Nature Comm. 7,11893 (2016).

Ratio of effort: Exp/Theo/Comp	Exp:	0	%
	Theo:	20	%
	Comp:	80	%

Suitability: BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: Laser and Optics, Classical Electrodynamics, some basic knowledge on computer programming such as C, C++, or Fortran and software for visualisation such as MATLAB would be helpful, but not essential.

Additional comments: No

Safety Training Requirements: No

Compact X-ray sources from nonlinear Thomson scattering with intense lasers

(1) Prof Zhengming Sheng , (2) Dr Feiyu Li

Project Description:

X-ray sources are widely used in scientific research, industry, and medicine. Well-known X-ray sources include X-ray tube, synchrotron radiation, X-ray free electron lasers, etc. With the advent of ultrashort high power, one can obtain compact X-ray sources in various new ways.

This project aims to develop a theory model together with corresponding numerical simulation to study the production of ultrashort X-ray sources from nonlinear Thomson scattering. In particular, an all-optical scheme will be considered, in which electrons will be first accelerated by an intense laser pulse and subsequently they are used to scatter the second intense laser pulse (or two intense lasers) for X-ray generation. In this project, the student will focus on the scattering processes. By the end of the project, the student will become familiar with the laser acceleration of a test electron in vacuum and familiar with the calculation of temporal and angular distributions of the X-ray radiations from the scattering of an energetic electron from intense laser pulses.

Key References:

1. W.-M. Wang, Z.M. Sheng et al., Phys. Rev. ST-AB 13, 071301 (2010).
2. S. Corde et al., Rev. Mod. Phys. 85, 1-48 (2013).
3. K. Ta Phuoca et al., Eur. Phys. J. D 33, 301–306 (2005).
4. S. P. Goreslavskii et al., Laser Physics 9, 1039–1044 (1999).
5. Y. Y. Lau et al., Phys. Plasmas 10, 2155-2162 (2003).
6. W. Yan et al., Nature Photonics 11, 514–520 (2017).

Ratio of effort: Exp/Theo/Comp

Exp:	0	%
Theo:	20	%
Comp:	80	%

Suitability: BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: Classical Electrodynamics, some basic knowledge on computer programming either with C, C++, or Fortran, or MATLAB for simulation and visualisation is essential.

Additional comments: No.

Safety Training Requirements: No.

High harmonics and attosecond radiation from laser interaction with a solid target

(1) Prof Zhengming Sheng, (2) Dr Feiyu Li

Project Description:

Recently with the development of chirped pulse amplification (CPA) technology, one can produce ultrashort and high intensity laser pulses. Such laser pulses can push electrons to relativistic quiver motion, and thereby produce X-ray sources via various schemes.

One scheme is based upon intense laser solid interaction. It is found that free electrons at the solid surface can be driven into relativistic oscillations in the incident laser fields. As a result, high harmonics of the laser pulse will be produced. When the solid target is very thin such as a few nano-meters, the high harmonics generation enters a new regime called coherent synchrotron radiation, where attosecond (1 attosecond=10-15s) light pulses may be produced.

In this project, the student will use some well-developed numerical simulation tool---a particle-in-cell code, to investigate high harmonics generation in different regimes or conditions.

Key References:

1. R. Lichters, J. Meyer-ter-Vehn, & A. Pukhov, Phys. Plasmas 3, 3425 (1996).
2. H.-C. Wu, Z.-M. Sheng et al., Phys. Rev. E 75, 016407 (2007).
3. S. Cousens, B. Reville, B. Dromey, and M. Zepf, Phys. Rev. Lett. 116, 083901 (2016).
3. U. Wagner et al., Phys. Rev. E 70, 026401 (2004).
4. M. Tatarakis et al., Nature (London) 398, 489 (2002).

Ratio of effort: Exp/Theo/Comp	Exp:	0	%
	Theo:	20	%
	Comp:	80	%

Suitability: BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: Laser and Optics, Classical Electrodynamics, some basic knowledge on computer programming such as C, C++, or Fortran and software for visualisation such as MATLAB would be helpful, but not essential.

Additional comments: No.

Safety Training Requirements: No.

Nanoscience Division

Noble Metal Quantum Dots

(1) Dr Yu Chen, (2) Dr Olaf Rolinski

Project Description:

Nanoscale noble metal particles have unique properties different from bulk. Indeed, small metal nanoclusters of sizes comparable to the Fermi wavelength of electrons (ca. 0.7 nm), no longer possess metallic properties, but have molecule-like behaviour including size-dependent luminescence [1] and discrete electronic states [2]. Recent advances in this area have seen the development of a variety of syntheses that produced a new class of fluorescent noble-metal quantum dots such as Au and Ag nanoclusters [3]. These nanosized emitters have great potentials in biological imaging and sensing because of their small sizes, tunable optical properties and low toxicity. This project intends to develop protein encapsulated gold quantum dots and explore their applications in biological sensing using optical spectroscopies.

Key Reference:

J. Zheng, C. W. Zhang and R. M. Dickson, Phys. Rev. Lett. **93**, 077402 (2004).
S. Chen, R. S. Ingram, M. J. Hostetler, J. J. Pietron, R. W. Murray, T. G. Schaaff, J. T. Khoury, M. M. Alvarez and R. L. Whetten, Science **280**, 2098 (1998).
R. Jin, H. Qian, Z. Wu, Y. Zhu, M. Zhu. A. Mohanty and N. Garg, J. Phys. Chem. Lett. ***1****, 2903 (2010).*

Ratio of effort: Exp/Theo/Comp	Exp:	95%
	Theo:	5%
	Comp:	0%

Suitability: MPhys, BSc

Safety Training Requirements: laser safety

Pathological modifications in proteins detected by their intrinsic fluorescence

(1) Dr Olaf Rolinski , (2) Dr Yu Chen

Project Description:

Protein glycation consists on multiple modifications of proteins by carbohydrates. During glycation protein-carbohydrate reactions lead to formation of several intermediate forms, then, through different pathways, give rise to so called advanced glycation end-products (AGEs). AGEs may be involved in different forms of pathophysiology if the original function of the protein has been compromised. Despite broad implications of glycation in human health (it is related to disorders like diabetes, inflammation, neurodegenerative diseases and to human ageing), the formation of glycated proteins is poorly investigated.

In this project the methods of fluorescence spectroscopy will be applied to investigate the process of molecular-level glycations related to different diseases, e.g. complications of diabetes mellitus, cataract and skin ageing. The student will develop his/her skills in a number of research techniques used in Photophysics group: non-routine use of the up-to-date fluorescence instrumentation, modelling fluorescence kinetics in complex environment, numerical data analysis, and molecular medicine.

Key References:

1. K.Nomoto et al., Identification of advanced glycation endproducts derived fluorescence spectrum in vitro and human skin, Anti-Aging Medicine, **10**(5),92-100 (2013).
2. D.K.Karumanchi et al., Non-enzymatic glycation od alpha-crystallin as an invitro model for aging, diabetes and degenerative diseases, Amino Acids, **47**, 2601-2608 (2015).

Ratio of effort: Exp/Theo/Comp

Exp:	80%
Theo:	10%
Comp:	10%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: Attending PH554 class in the second semester (fluorescence part) is recommended.

Additional comments: The student needs to enjoy the analytical aspect of physics experimentation.

Safety Training Requirements: The lecture “Introduction to laboratory safety” provided by the Photophysics Group in compulsory before the experimental part can be undertaken.

Characterisation and implementation of computational super-resolution algorithms

Brian Patton(1) , Sebastian Van de Linde(2)

Project Description:

Super-resolution microscopy won the Nobel prize in Chemistry in 2014 for allowing imaging of objects beyond the classical diffraction limit. We are performing research into multiple versions of super-resolution microscopy, including Stimulated Emission Depletion (STED) and Single Molecule Localisation techniques.

The realisation that the diffraction limit can be overcome by appropriate imaging methods has led to a wide variety of super-resolution techniques that vary in their experimental and analytical complexity.

One approach that appears to produce excellent results is known as Super-Resolution Radial Fluctuation (SRRF) imaging and involves an algorithm that can be applied to multiple-image stacks acquired by a wide range of microscopes.

This project is an investigation of the practicalities of implementing SRRF on super-resolution microscopes being constructed in the department. In order to generate some initial test data, a simple microscope will be constructed and images captured by it will be analysed with the SRRF algorithm. If successful, the student will also be able to request images from our research microscopes to test the effectiveness of SRRF on data-sets from super-resolution microscopes.

Key References: "Fast live-cell conventional fluorophore nanoscopy with ImageJ through super-resolution radial fluctuations", N. Gustafsson et al., DOI: 10.1038/ncomms12471M

"Super-resolution microscopy at a glance", C. G. Galbraith and J.A. Galbraith, DOI:10.1242/jcs.080085

Ratio of effort: Exp/Theo/Comp

Exp:	30%
Theo:	30%
Comp:	40%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites:

Additional comments: Experience of programming is strongly advised, experience of optical design would be helpful but not essential. Some experience of data analysis with Matlab would also be beneficial.

Safety Training Requirements: Low power laser diodes may be required, so Laser Safety Training is essential.

Development of a Phase Contrast Imaging system for use with an in-development low-cost, open-access detector for water quality

Brian Patton (1), Stephen Grant (2)

Project Description:

Harmful Algal blooms (HABS) are events where a massive increase in the amount of algae in a water body causes illness, environmental damage, or loss of income due to lost livestock (for fish and shellfish farmers) and reduced tourism. Current methods of testing and responding to algal blooms are based on technically demanding chemical techniques and expensive equipment. We are aiming to develop a low-cost, open-access optical detector to allow people in developing nations access to an effective and robust diagnostic tool to predict occurrences of HABS and act accordingly to minimise their negative effects.

Phase contrast imaging is commonly used in biological applications to allow detailed imaging of highly transparent samples by taking advantage of differences in refractive index in the structures within the sample. This project aims to test a method to include phase contrast imaging in the proposed device using components that are low cost and can be easily obtained. We will be basing the technique on the paper below, but adapting it for the unique requirements of our HABS sensor.

The project will involve optical design of the phase contrast imaging system. There will potentially be some mechanical design to develop a housing for the optics involving 3D modelling and 3D printing. A small amount of programming and electronics may be involved to control the illumination system and to facilitate data collection and analysis.

Key References: Webb, Kevin F. "Condenser-free contrast methods for transmitted-light microscopy." Journal of microscopy (2015).

Ratio of effort: Exp/Theo/Comp

Exp:	50%
Theo:	30%
Comp:	20%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites:

Additional comments: Experience of optical design, 3D modelling (SolidWorks, Blender), and programming (Python, Matlab) would be helpful but not essential. Some experience of data analysis with Matlab and ImageJ would also be beneficial.

Safety Training Requirements: Laser Safety Training is required due to the nature of the other work performed in the group.

Calibration of Spatial Light Modulators for Adaptive Optics Microscopy

Brian Patton(1) , (2)

Project Description:

Super-resolution microscopy won the Nobel prize in Chemistry in 2014 for allowing imaging of objects beyond the classical diffraction limit. We are performing research into adaptive optical technologies to improve the performance of planned super-resolution microscopes that will be contrasted and operated within the department.

Adaptive optics uses dynamically controlled components to correct for optical aberrations in an imaging system, restoring near-perfect performance. In the context of microscopy, it allows imaging deep into tissue, where the inhomogeneous refractive index causes problems for standard microscopes. The liquid-crystal spatial light modulator (SLM) is one class of device that finds widespread use in adaptive optics enhanced microscopy. However, in order to correctly incorporate the SLM into the design of the microscope, it is necessary to know its optical performance parameters such as the optical flatness of the device and the magnitude of optical-phase change induced by each pixel of the device. This project involves setting up an interferometric characterisation apparatus to evaluate the performance of a low-cost, but useful, SLM. The project will entail optics design, programming of some software to drive the SLM and analysis of the data derived from the setup.

Key References: "Optimisation of a low cost SLM for diffraction efficiency and ghost order suppression", R. Bowman et al., DOI: 10.1140/epjst/e2011-01510-4

M. J. Booth, "Adaptive optical microscopy: the ongoing quest for a perfect image," Light Sci. Appl. 3, 165 (2014)

Ratio of effort: Exp/Theo/Comp	Exp:	40%
	Theo:	20%
	Comp:	40%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites:

Additional comments: Experience of programming is strongly advised, experience of optical design would be helpful but not essential. Some experience of data analysis with Matlab would also be beneficial.

Safety Training Requirements: Low power laser diodes will be required, so Laser Safety Training is essential.

Can techniques from nanoscale imaging help millimetre scale mesoscopy?

(1) Dr. Brian Patton, (2) Prof. Gail McConnell

Project Description:

Lightsheet imaging involves the generation and application of a thin light sheet to excite fluorescence from a specimen that is subsequently detected orthogonally using high speed, high resolution digital cameras [1]. There are multiple advantages to light sheet imaging that make it particularly exciting when used in conjunction with the Mesolens, a giant, high resolution lens which can provide sub-cellular resolution images with an image volume of more than 110 mm^3 [2]. However, making a multi-mm wide light sheet that is simultaneously only a few microns thick is a difficult challenge.

One potential approach uses STimulated Emission Depletion techniques, which were originally developed to image objects only tens of nanometers across. By using a second laser beam with a specially shaped focus, it is possible to engineer the shape of the region which is being imaged and to overcome some of the limitations of more conventional optical approaches.

Following a review of the literature, the student will use a set of software that uses vectorial diffraction approaches [3] to explore the effect of differing depletion beam characteristics on the predicted lightsheet parameters. By comparing the optimal theoretical designs with the performance characteristics of the Mesolens and of advanced light-control hardware available to researchers in Strathclyde we hope that this project will help us design a lightsheet unlike anything elsewhere in the world!

Key References:

[1] “Light sheet-based fluorescence microscopy (LSFM) for the quantitative imaging of cells and tissues”, F. Pampaloni et al, Cell Tissue Res. 360, 129 (2015)

[2] “A novel optical microscope for imaging large embryos and tissue volumes with sub-cellular resolution throughout”, G. McConnell et al, eLife 5 e18659 (2016)

[3]” Fast vectorial calculation of the volumetric focused field distribution by using a three-dimensional Fourier transform”, J. Lin et al, Opt. Exp. 20, 1060 (2012)

Ratio of effort: Exp/Theo/Comp

Exp:	20%
Theo:	30%
Comp:	50%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites:

Additional comments: Experience of optical design, and programming (Python, Matlab) would be helpful but not essential. Some experience of data analysis with Matlab and ImageJ would also be beneficial.

Safety Training Requirements: Laser Safety Training is required due to the nature of the other work performed in the group.

Automated Image Analysis in Single-Molecule Localization Microscopy

(1) Dr Sebastian van de Linde, (2) Dr Oliver Henrich

Project Description:

Recently, different super-resolution microscopy have methods emerged that overcome the diffraction limit of light microscopy as evidenced by the Nobel Prize awarded for this work in 2014. A very powerful variant is single-molecule localization microscopy (SMLM) that achieves a lateral resolution down to 20 nm.

SMLM is a wide-field based imaging technique utilizing photoswitchable fluorophores, i.e. molecules that exhibit a transition between non-fluorescent off- and fluorescent on-states. Image generation is based on the acquisition and processing of a series of images, each of them containing different subsets of stochastically activated fluorophores.

With the aid of sensitive cameras, fluorophores are detected as diffraction limited spots as they are convolved with the point spread function (PSF) of the microscope. By fitting a two-dimensional Gaussian function to its emission profile, the centre of the molecule can be determined with nanometre precision. Finally, a super-resolution image is generated by merging all single-molecule coordinates into a single image.

Objectives of this project are an introduction to state-of-the-art SMLM software packages and image processing. Depending on progress and interest of the student software routines for (i) correcting experimental stage drift during image acquisition and/or (ii) averaging emission patterns of single molecules in order to characterize the experimental PSF of the super-resolution microscope will be developed.

Key References:

[1] C. G. Galbraith and J. A. Galbraith. *Super-resolution microscopy at a glance*. J. Cell Sci., 124, 1607 (2011).
[2] S. Wolter, M. Schuettpelz, M. Tscherepanow, S. van de Linde, M. Heilemann, M. Sauer. *Real-time computation of subdiffraction-resolution fluorescence images*. J. Microsc., 237, 12 (2010).
[3] A. Small and S. Stahlheber. *Fluorophore localization algorithms for super-resolution microscopy*. Nat. Methods, 11, 267 (2014).

Ratio of effort: Exp/Theo/Comp

Exp:	20 %
Theo:	20 %
Comp:	60 %

Suitability: MPhys, BSc, BSc Maths and Physics

Additional comments: Experience of programming is strongly advised. Experience of data analysis would also be beneficial.

Safety Training Requirements: Low power laser diodes will be required, so Laser Safety Training is essential.

Three-Dimensional Single-Molecule Based Super-Resolution Imaging

(1) Dr Sebastian van de Linde, (2) Dr Brian Patton

Project Description:

Super-resolution fluorescence microscopy methods emerged that overcome the diffraction limit of light microscopy as evidenced by the Nobel Prize awarded for this work in 2014. A very powerful super-resolution microscopy technique is single-molecule localization microscopy (SMLM) that achieves lateral and axial resolutions down to 20 nm and 30-100 nm, respectively.

SMLM is a based on localizing single-molecules with high precision. This can be achieved by fitting a two-dimensional Gaussian function to the shape of the emission and reconstructing a super-resolution image from thousands to millions of single-molecule localizations.

In this projects, two 3D techniques will be investigated; one is based on point spread function (PSF) engineering by introducing astigmatism, the other one is based on splitting and detecting single-molecule emission at different focal planes on the detector (biplane imaging). In both cases, the shape of the emission pattern is analysed and used to decode the axial position of the molecule.

The student will be introduced to state-of-the-art SMLM software packages and their 3D fitting capabilities. Appropriate calibrating standards using a z-piezo scanner will be developed and the performance of biplane and astigmatism based 3D SMLM methods on biological samples will be compared using different hardware configurations.

Key References:

[1] C. G. Galbraith and J. A. Galbraith, Super-resolution microscopy at a glance, *J. Cell Sci.*, **124**, 1607 (2011).
von Diezmann et al., Three-Dimensional Localization of Single Molecules for Super-Resolution Imaging and
[2] Single-Particle Tracking, *Chem. Rev.*, **117**, 7244 (2017).
[3] A. Small and S. Stahlheber, Fluorophore localization algorithms for super-resolution microscopy, *Nat. Methods*, **11**, 267 (2014)

Ratio of effort: Exp/Theo/Comp	Exp:	40 %
	Theo:	20 %
	Comp:	40 %

Suitability: MPhys, BSc, BSc Maths and Physics

Additional comments: Experience in programming and data analysis is recommended.

Safety Training Requirements: Low power laser diodes will be required, so Laser Safety Training is essential.

Large scale lattice-Boltzmann simulation of colloid-liquid crystal composite materials

(1) Dr Oliver Henrich, (2) Dr Benjamin Hourahine

Project Description:

Liquid crystals (LCs) are fascinating materials as they feature properties between those of simple liquids and solid crystals. They have been often referred to as the fourth state of matter and ushered in a technological revolution due to their unique capability to modulate visible light. The potential for technological applications is far from being exhausted as new areas emerge constantly, such as LC-based integrated lab-on-a-chip devices as well as micro- and optofluidic systems.

Common LC phases are unordered at high temperature, but undergo transitions to phases with positional and/or orientational order upon cooling. When nanometre-sized colloidal particles are introduced into the LC host phase, the local order gets distorted around the particles. This leads to so-called 'entangled states' where the LC acts like a glue between the particles [1-3], leading to complex collective dynamical effects. Such new materials allow new levels of control over their properties, but their behaviour is far from being understood.

In this project, we will study the flow of LC-colloid composite materials in microfluidic geometries [4] at unprecedented colloid volume fractions. These systems have promising potential for use in a new generation of optical encryption devices. We will use *Ludwig*, [5] a state-of-the-art lattice-Boltzmann code for simulation of complex fluids and deploy simulations on Strathclyde's local high-performance computing (HPC) service ARCHIE-WeST and on the UK national supercomputing service ARCHER.

Key References:

[1] J. S. Lintuvuori, K. Stratford, M. E. Cates and D. Marenduzzo , Colloids in Cholesterics: Size-Dependent Defects and Non-Stokesian Microrheology, *Phys. Rev. Lett.* **105**, 178302 (2010)
[2] M. Ravnik, S. Zumer, Nematic braids: 2D entangled nematic liquid crystal colloids*, Soft Matter* **5**, 4520 (2009).
[3] K. Stratford, O. Henrich, J. Lintuvuori, D. Marenduzzo, M.E. Cates, Self-Assembly of Colloid-Cholesteric Composites: A Route to Switchable Optical Materials, *Nat. Comm.* **5**, 3954 (2014).
[4] O. Wiese, D. Marenduzzo, O. Henrich, Microfluidic flow of cholesteric liquid crystals, *Soft Matter* **12**, 9223-9237 (2016).
[5] Ludwig: soft matter simulation software; https://github.com/ludwig-cf/ludwig

Ratio of effort: Theo/Com	Theo:	30%
	Comp:	70%

Suitability: 4th year MPhys

Recommended Classes/Pre-requisites: Experience with the UNIX command line user interface and a scripting language such as Python are strongly recommended.

Additional comments: This project requires familiarising with physical theory and simulation methodology that is relatively far away from the standard curriculum. Furthermore, technical aspects of this work include usage of top-end HPC facilities, version control systems and code repositories and visualisation tools. The project may therefore appeal to committed students with a keen interest in computational physics, soft condensed matter, material science and/or computational fluid dynamics and potentially also those who are looking for ways to enhance their IT skills and willing to work hard.

Safety Training Requirements: N/A

Investigation of Polytypism in nitride semiconductors

(1) Dr Carol Trager-Cowan, (2) Dr Naresh-Kumar, Dr Jochen Bruckbauer

Project Description:

GaN usually grows with the thermodynamically stable wurtzite (2H) crystal structure; however, it can also be grown with the zinc blende (3C) crystal structure. Certain growth conditions result in GaN thin films containing both crystal structures (polytypes). Recent research at Strathclyde, involving the mapping of the light emitting properties (using cathodoluminescence (CL)) of a series of micro-patterned semi-polar GaN thin films, have indicated that it may also be possible to produce GaN with the 4H and 2H crystal structures. These are polytypes intermediate between wurtzite and zinc blende. The advanced scanning electron microscopy (SEM) technique of electron backscatter diffraction (EBSD) provides information on the structural properties of materials rapidly and non-destructively with a spatial resolution of tens of nanometers. In particular, the interpretation of the acquired EBSD patterns allows the orientation, crystal structure and strain distribution in a sample to be mapped. In this case we are interested in mapping the crystal structure of GaN thin films which exhibit more than one crystal structure. The aim of this project is to compare simulated EBSD patterns with provided experimental EBSD patterns from a number of GaN thin films in order to understand their crystallography. The simulations will be produced using the many-beam dynamical simulation software ESPRIT DynamicS developed by one of our collaborators (Bruker Nano, Berlin). Comparison with CL datasets will also allow the crystallographic properties to be correlated with the materials' light emitting properties.

Key References:

[1] http://ssd.phys.strath.ac.uk/
[2] https://www.bruker.com/products/x-ray-diffraction-and-elemental-analysis/eds-wds-ebsd-sem-micro-xrf-and-sem-micro-ct/esprit-dynamics/overview.html

Ratio of effort: Exp/Theo/Comp	Exp:	5%
	Theo:	30%
	Comp:	65%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH453 Topics in Solid State Physics, PH454 Topics in Nanoscience

Additional comments: This project is open to more than one student.

Safety Training Requirements: None.

Computing the inverse square law

(1) Dr Ben Hourahine, (2) Dr Oliver Henrich

Project Description:

Interactions proportional to $1/r^2$ occur in gravitational, electrostatic and electromagnetic interactions, where r is the separation between bodies. The slow decrease of this function with distance causes major challenges when there are large numbers of interacting objects. Every possible pair of particles in the system contributes to the total interaction, so for N particles there are N^2 contributions.

One of the major computational breakthroughs in the 20th Century [1] was to realise that instead of considering each pair of particles, at larger distances only the net contributions from groups of particles matters. This leads to methods that evaluate a total of either $N \log N$ interactions [2], or even better only N [3] terms. This has enabled simulations of up to $\approx 10^{12}$ particles on large supercomputers for application in cosmology or materials and bio-science.

This project will investigate using these smarter ways to calculate the forces between interacting particles, and see if it is possible to use $< N$ terms in evaluating their interactions.

Key References:

[1] B. A. Cipra (May 16, 2000). "The Best of the 20th Century: Editors Name Top 10 Algorithms". SIAM News. Society for Industrial and Applied Mathematics. 33 (4): 2.
[2] J. Barnes and P. Hut. "A Hierarchical O(N log N) Force-Calculation Algorithm". Nature 324, 446–449 (1986).
[3] J. Carrier, L. Greengard, and V. Rokhlin. A Fast Adaptive Multipole Algorithm for Particle Simulations. SIAM J. Sci. and Stat. Comput. 9, 669–686 (1988).

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	40%
Comp:	60%

Suitability: MPhys, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH456 Topics In Computational And Complex Systems In Physics

Additional comments: This project is open to more than one student.

Safety Training Requirements: N/A

Optical Modes and Multiple Scattering

(1) Dr Ben Hourahine, (2) Dr Francesco Papoff

Project Description:

It has recently been shown that the optical properties of most nano-particles can be understood as arising from the modes of the particle. These are, like the standing acoustic waves of an organ pipe or the wavefunctions of a quantum mechanical particle in a box, distinct solutions of the appropriate wave equations (here, Maxwell's equations). However, if a second particle is brought close by, how does this affect these modes?

Light will then "bounce" between these two particles (multiple scattering), leading to a new set of optical modes which describe the whole composite system. This project will theoretically and computationally study the transition between the isolated and coupled modes of two glass particles as they approach each other.

Key Reference (if applicable):

F. Papoff, B. Hourahine, Geometrical Mie theory for resonances in nanoparticles of any shape, Optics Express, 19, 21432 (2011)

Ratio of Experiment/Theory/Computation:	**Exp:**	**0%**
	Theo:	**50%**
	Comp:	**50%**

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites:

Additional comments: This project is open to more than one student.

Optics Division

Beam Quality of Broad-area Diode Lasers

(1) Prof Thorsten Ackemann, (2) Dr Michael Strain

Project Description:

Power scaling of semiconductor laser diodes and maintaining at the same time a high beam quality is a notoriously difficult challenge, since increasing the emission aperture leads to numerous instabilities limiting the brightness of a broad-area laser (BAL) [2].

Recently, a novel approach to control the beam quality of edge-emitting BALs maintaining their attractive monolithic compactness was proposed [1]. The suggestion is to implement a two-dimensional spatial modulation- *simultaneously transverse and parallel to the cavity axis* – of the gain characteristics, i.e. of the imaginary part of the susceptibility, by a modulation of the current injection. Similar to the case of photonic crystals (relying on a modulation of the real part of the susceptibility), the modulation is predicted to lead to a modification of spatial dispersion curves, in particular to a spatial filtering and a highly directional gain along the optical axis. As a result, *noise triggered by inhomogeneities or dynamically generated via instabilities* is quenched.

The project will set up a probe station to measure beam quality of BALs and perform measurements of samples processed at the University of Glasgow.

Key Reference:

[1] R. Herrero et al., Beam shaping in spatially modulated broad-areasemiconductor amplifiers, Opt Lett. 37, 5253 (2012);

[2] Crump et al., Experimental and theoretical analysis of the dominant lateral waveguiding mechanism in 975 nm high power broad area diode lasers. Semicond. Sci. Technol. ***27*** *(2012) 045001*

Ratio of effort: Exp/Theo/Comp	Exp:	70%
	Theo:	10%
	Comp:	20%

Suitability: MPhys, BSc

Additional comments: *The student is required to attend PH445 and PH453 to obtain the necessary background.*

Safety Training Requirements: *laser*

Characterization of optically pumped quantum well and quantum dot vertical-cavity structures

(1) Prof Thorsten Ackemann, (2) Dr Antonio Hurtado

Project Description:

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. 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. Most work centred on relatively low gain structures in vertical-cavity surface-emitting lasers (VCSEL) with quantum well gain media.

This project will look at high gain quantum well samples for external-cavity use (VECSELs) and VCSEL structures containing quantum dots, zero dimensional semiconductors with quantum confinement in all directions. The measurements will start with analyzing the polarization properties of the photoluminescence in dependence on the polarization ellipticity of the optical pump field. Polarization dependent gain will be measured afterwards via a tunable laser. The final aim of the project is to achieve lasing.

Key Reference:

[1] Bhattacharya et al., Quantum dot polarized light sources, Semicond. Sci. Technol. 26 (2011) 014002
[2] Hoevel et al., Appl. Phys. Lett. 92, 041118 (2008)

Ratio of effort: Exp/Theo/Comp

Exp:	70%
Theo:	15%
Comp:	15%

Suitability: MPhys, BSc

Additional comments: The student is required to attend PH445 and PH453 to obtain the necessary background. The project demands the engagement with tedious and careful optical alignment.

Safety Training Requirements: laser

Observing Beam Propagation by Fluorescence

(1) Dr Aidan Arnold, (2) Dr Paul Griffin

Project Description:

You will make a thorough investigation of the Beer-Lambert Law (and its generalisation) by imaging the fluorescence (spontaneous emission) of rubidium atoms in a vapour cell to detect the local intensity of laser beams propagating through the 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.

Key Reference: *N. Radwell, M. A. Boukhet, and S. Franke-Arnold, Opt. Express **21**, 22215 (2013).*

Ratio of effort: Exp/Theo/Comp	Exp:	70%
	Theo:	20%
	Comp:	10%

Suitability: MPhys

Additional comments: *Lab JA3.04A*

Safety Training Requirements: *Laser safety training required.*

Grating magneto-optical trap modelling

(1) Dr Aidan Arnold, (2) Dr Paul Griffin

Project Description:

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 [2-5].

In this project you will model the acceleration in both forms of magneto-optical trap to see how the atom number collected scales with laser input power. An ideal extension of this project will be to compare your theoretical results to the lab experiments.

Key References:

[1] E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard, *Trapping of Neutral Sodium Atoms with Radiation Pressure*, Phys. Rev. Lett. 59, 2631 (1987).

[2] M. Vangeleyn, P.F. Griffin, E. Riis and A.S. Arnold, *Single-laser, one beam, tetrahedral magneto-optical trap*, Opt. Express **17**, 13601 (2009).

[3] M. Vangeleyn, P.F. Griffin, E. Riis, and A.S. Arnold, *Laser cooling with a single laser beam and a planar diffractor*, Opt. Lett. **35**, 3453 (2010).

[4] C.C. Nshii *et al*., *A surface-patterned chip as a strong source of ultracold atoms for quantum technologies*, Nature Nanotech. **8**, 321 (2013).

[5] J.P. McGilligan, P.F. Griffin, E. Riis, A.S. Arnold, *Phase-space properties of magneto-optical traps utilising micro-fabricated gratings*, Opt. Express **23**, 8948 (2015).

Ratio of effort: Exp/Theo/Comp

Exp:	20%
Theo:	20%
Comp:	60%

Suitability: MPhys only

Recommended Classes/Pre-requisites: PH355 Physics Skills

Additional comments:

Safety Training Requirements: Laser safety training will be provided.

Propagation of orbital-angular momentum beams through a scattering medium

(1) Dr Paul Griffin, (2) Dr David McKee

Project Description:

Light with an electric-field pattern. in either amplitude or phase, that varies across the transverse dimension has applications in a range of fields; telecommunications, quantum information, optical trapping of living cells, single-pixel cameras, and measurement of turbulence, to select but a few. This project will use spatial light modulators (SLMs) as a rapid and robust method of generation of such light beams from standard laser systems. The project will examine how such beams propagate and how their subsequent detection can be used for measurement of physically interesting properties, such as measurement of particles and turbulence in water and in air

Key References:

[1] "A.M. Yao, and M.J. Padgett, "Orbital angular momentum: origins, behaviour and applications", Advances in Optics and Photonics, 3 (2). p.161, (2011)

[2] Wikipedia key topics: "Orbital angular momentum of light," "Transmissometer", "Mie scattering"

Ratio of effort: Exp/Theo/Comp

Exp:	60%
Theo:	30%
Comp:	10%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH355 Physics Skills

Additional comments: This project is suitable primarily for a student with a strong interest in experimental physics.

Safety Training Requirements: Laser safety training will be provided.

Atomic Physics Game Design for Outreach Activities

(1) Dr Stuart Ingleby, (2) Dr Paul Griffin and Dr Gordon Robb

Project Description:

Atomic physics and quantum technologies, such as optically pumped magnetometers, atomic clocks and rotation sensors, are increasingly important in real-world applications [1]. It is important to communicate effectively with the public on the advantages, operation and scientific basis of these technologies. However, the underlying physics is not always intuitively easy to understand. In this project you will develop a console-type game allowing members of the public to play with the atomic system and visualise how the sensor works.

A physics-based game should have several advantages over other demonstration activities. We have observed that people engage much more with things that they can interact directly with, and the graphical interface of a game can be used to visualise the system physics more readily than a model or image display. By using robust, durable controllers, a game can be made suitable for visitors of all ages, including schoolchildren. Your game should meet the following criteria:

- Accurately represent the physics of the atomic sensor system (e.g. the precession of alkali atoms in an optically pumped magnetometer).
- Have simple, intuitive controls that can be learned in a few seconds.
- Have an attractive and polished graphical appearance suitable for display on monitors of varying sizes.
- Run on a portable computer, such as a Raspberry Pi.

Key References:

[1] Roadmap on quantum optical systems, R Dumke *et al.*, J. Opt. **18** 093001 (2016)

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	40%
Comp:	60%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: PH355 Physics Skills

Additional comments:

Safety Training Requirements:

Domain Walls in Optical Fibre Resonators

(1) Prof Gian-Luca Oppo, (2) Dr Alison Yao

Project Description:

Domain walls (also known as kinks) separate regions of different physical behaviours in magnetic systems, in chains of coupled pendula and in collision-less plasmas. In the optical domain, domain walls have been described in the plane perpendicular to the propagation of laser beam for coupled waves with orthogonal polarization and in optical parametric oscillators [1]. Recent developments have shown that nonlinear features in the transverse plane have one-to-one counterparts in optical fibres in resonators [2].

This project aims at investigating domain walls between left and right circular polarizations in an optical fibre resonator. In particular, we study and compare the formation of periodic structures, locked domain walls and solitons in theoretical and computational models of polarized light propagating in fibres with or without an optical resonator. The project is done in collaboration with experiments carried out at the University of Auckland (New Zealand).

Key References:

[1] R. Gallego et al., "Self-similar domain growth, localized structures, and labyrinthine patterns in vectorial Kerr resonators", Phys. Rev. E **61**, 2241 (2000); G.-L. Oppo et al, "Characterization, dynamics and stabilization of diffractive domain walls and dark ring cavity solitons in parametric oscillators"**,** Phys. Rev. E **63**, 066209 (2001)

[2] J.K. Jang et al., "Controlled merging and annihilation of localised dissipative structures in a driven damped nonlinear Schrödinger system" New Journal of Phys. **18**, 033034 (2016)

Ratio of effort: Exp/Theo/Comp		
	Exp:	0 %
	Theo:	40 %
	Comp:	60 %

Suitability: MPhys, BSc Maths and Physics

Recommended Classes/Pre-requisites:

Additional comments: The project requires skills in mathematical and computational techniques.

Safety Training Requirements: None.

Opto-mechanics of Bose-Einstein Condensates in Optical Cavities

(1) Prof Gian-Luca Oppo, (2) Dr Gordon Robb

Project Description:

Bose-Einstein Condensates (BEC) inside an optical cavity and under the action of a coherent laser, can display exotic oscillations and even deterministic chaos [1]. This is quite unexpected for a quantum gas moving along the cavity via the tunnelling effect, a purely quantum phenomenon. The chaotic oscillations can also be enhanced by small modulations of the driving laser amplitude [1].

This project aims at investigating a new physical state of BEC in optical cavities. When the cavity finesse is increased, experiments in Hamburg have revealed that opto-mechanics with resonant momentum transfer takes place [2]. This results in the BEC atoms moving from zero to quantised momenta in a sequence of modal jumps. We investigate this phenomenon via theoretical and simulation methods to discover the basic mechanisms that combine cavity scattering and strong coupling between light and ultra-cold atoms. Please note that numerical codes are already in operation.

Key References:

[1] M. Diver, G. R. M. Robb, and G.-L. Oppo, "Nonlinear and chaotic dynamics of a Bose-Einstein condensate in an optical cavity", Phys. Rev. A 8**9**, 033602 (2014) and "Chaotic resonances of a Bose-Einstein condensate in a cavity pumped by a modulated optical field", Phys. Rev. A **91**, 033622 (2015)

[2] H. Keßler et al., "Optomechanical atom-cavity interaction in the sub- recoil regime", New Journal of Physics **16,** 053008 (2014)

Ratio of effort: Exp/Theo/Comp

Exp:	0 %
Theo:	40 %
Comp:	60 %

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites:

Additional comments: The project requires skills in mathematical and computational techniques.

Safety Training Requirements: None.

Soliton Glass

(1) Prof Gian-Luca Oppo, (2) Dr Francesco Papoff

Project Description:

Spatial optical solitons are beams of light in which nonlinearity counter-balances diffraction, leading to robust single-hump structures that propagate without change of form. In the case of light propagating through a medium, the simplest spatial soliton is due to self-focusing and Kerr nonlinearity, that is, a refractive index which changes in proportion to the intensity of the light. More general schemes where dissipation and driving are included can also support stable soliton-like solutions with lots of intriguing and new properties. Among these, localized bright spots in driven-optical cavities have received a great deal of attention because of their applications in information processing [1].

This project aims at investigating a new physical state for spatial optical solitons: a glass. Normal spatial solitons in random positions are susceptible to background noise fluctuations and can be described as a soliton gas. Above certain thresholds, however, spatial solitons in media pumped by two laser beams [2] can freeze at certain distances and form conglomerates similar to those observed in amorphous media such as glass. Characterization of the soliton glass phase, its origin and possible melting are among the objectives of the project. Please note that numerical codes are already in operation.

Key References:

[1] T. Ackemann, W. J. Firth and G-L Oppo, "Fundamentals and Applications of Spatial Dissipative Solitons", Adv. At. Mol. Opt. Phys. **57**, 323 (2009)

[2] M. Esalmi et al., "Complex structures in media displaying electromagnetically induced transparency: Pattern multistability and competition", Phys. Rev. A **90**, 023840 (2014)

Ratio of effort: Exp/Theo/Comp		
	Exp:	0 %
	Theo:	40 %
	Comp:	60 %

Suitability: MPhys, BSc Maths and Physics

Recommended Classes/Pre-requisites:

Additional comments: The project requires skills in mathematical and computational techniques.

Safety Training Requirements: None.

Cold Atom-Light Interactions

(1) Dr Gordon Robb, (2) Dr Brian McNeil

Project Description:

It is now possible to cool atoms down to temperatures close to absolute zero. At these temperatures, the interaction between light and atoms can change dramatically; with the optical forces acting on the atoms can play a significant effect.

The project will involve analysing and simulating interactions between optical beams and a gas of cold atoms, in particular considering cases where the light-atom interaction is nonlinear, offering new possibilities for e.g. optical pattern formation, light amplification and atomic self-organisation.

Key Reference:

E. Tesio, G.R.M. Robb, T. Ackemann, W.J. Firth, and G.-L. Oppo, Phys. Rev. A 86, 031801(R) (2012)

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	30%
	Comp:	70%

Suitability: MPhys BSc

Additional comments: *This project may be run simultaneously with 2 students in parallel.*

Bose Einstein Condensate (BEC) Simulations

(1) Dr Gordon Robb, (2) Dr Aidan Arnold

Project Description:

When a gas of atoms is cooled to a temperature < ~1μK , it can stop behaving as a cloud of classical particles and instead behave as a “matter wave” or Bose-Einstein Condensate (BEC), whose behaviour is governed by the laws of quantum mechanics [1]. BECs were first realised experimentally in 1995 and the only one in Scotland is here at Strathclyde.

This project will involve theory and simulation of a BEC in a storage ring [2].

References :

[1] Allan Griffin, D. W Snoke, S Stringari , Bose-Einstein condensation
Cambridge, New York : Cambridge University Press (1995).

[2] A. S. Arnold, C. S. Garvie, and E. Riis, Phys. Rev. A 73, 041606(R) (2006)

Ratio of Experiment/Theory/Computation:	Exp:	0 %,
	Theo:	50 %
	Comp:	50 %

Suitable for: PH450 MPhys BSc

Additional Comments: *Some experience of programming would be preferred, but is not essential.*

Safety Training Requirements: *Contact the project Supervisor for further advice*

Interactive Physics Simulations

(1) Dr Gordon Robb, (2) Dr Nigel Langford

Project Description:

Many interactive Physics simulations have been developed over the years in a variety of different languages e.g. JAVA, Adobe Flash, Shockwave etc.

However, for several reasons many existing simulations have now become obsolete, e.g.

- Most modern browsers do not run JAVA easily, as it is perceived as a security risk
- Many existing simulations cannot run on tablets or mobile phones

The project will involve developing one or more interactive Physics simulations using HTML5, which allows them to be run on modern browsers and on mobile devices. Recent examples of such simulations and teaching activities which use them can be found in [1].

The physics topic and the exact method of developing the simulation can be adjusted to suit the student's degree programme and level of previous programming experience.

Key Reference: *https://phet.colorado.edu*

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	20%
	Comp:	80%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Additional comments:

Safety Training Requirements: *N/A*

Creation and control of continuous-mode optical superposition qubits

(1) Prof John Jeffers, (2) Dr Luca Mazzarella

Project Description:

The creation and coherent control of qubits, the quantum version of the bit, is a fundamental task in quantum information processing. The no-cloning theorem [1], a fundamental result of quantum mechanics, forbids the perfect creation of a state that is orthogonal to an unknown quantum state (i.e. the implementation of a NOT gate). In contrast we can in principle realize a perfect orthogonalizer even if we only know some limited preliminary information about the input state, most notably if we know its expectation value with respect to a particular operator [2].

A coherent state is a quantum state of the electromagnetic field that can represent a laser pulse and therefore can be easily generated and manipulated. Recent work [3][4][5] proved the ability to create the state orthogonal to an unknown coherent state, based on the sole knowledge of the coherent state's mean photon number. An arbitrary superposition of the coherent state and its orthogonal counterpart can also be created, such for example the so called Schrödinger cat state [6].

The aim of this project is to investigate how this tool can be generalized and used in optical quantum information processing to create and control optical qubits composed of a superposition of a coherent state and its orthogonal counterpart. The project will be comprised of two parts. The first will focus on a theoretical investigation based on standard quantum optical tools, possibly aided with some simulation. In the second part, the findings of the first part will be used to design an experiment.

Key References:

[1] W. Wootters, and W. Zurek, A single quantum cannot be cloned, Nature 299, 802-803 (1982).
[2] M. R. Vanner, M. Aspelmeyer, and M. S. Kim, Quantum State Orthogonalization and a Toolset for Quantum Optomechanical Phonon Control, Phys.Rev. Lett 110, 010504 (2013).
[3] A.S. Coelho, L.S. Costanzo, A. Zavatta, C. Hughes, M.S. Kim, and M. Bellini, Universal continuous-variable state orthogonalizer and qubit generator, Phys. Rev. Lett., 116, 110501 (2016)
[4] A. Zavatta, V. Parigi, M. S. Kim, H. Jeong, & M. Bellini, Experimental demonstration of the bosonic commutation relation via superpositions of quantum operations on thermal light fields. Phys. Rev. Lett. 103, 140406 (2009)
[5] A. Zavatta, S. Viciani, and M. Bellini, Single- photon excitation of a coherent state: Catch- ing the elementary step of stimulated light emission, Phys. Rev. A 72, 023820 (2005).
[6] E. Schrödinger, Die gegenwärtige Situation in der Quantenmechanik, Naturwissenschaften 23, 807-812 (1935).

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	80%
Comp:	20%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites:

Additional comments:

Safety Training Requirements:

Optimisation of secure imaging

(1) Prof John Jeffers, (2) TBC

Project Description:

This project concerns security against jamming in imaging based on quantum mechanics. Due to indistinguishability of quantum states of photons' polarisation legitimate imagers who prepare the states have an informational advantage over an intruder. Our aim is to recognise optimal strategies of the imagers to detect the intrusion. We will analyse the scenario with two non-orthogonal polarisation states. In this case, the optimal scenario of the intruder is related to the Helstrom formula for the probability of correct discrimination between the states. Knowing this, we can recognise the best strategy of the imagers to detect the intrusion and deliver analytical formulas for the detection probability. The project can be extended on more complicated situations.

Key References:

1. W. Roga, J. Jeffers, Security against jamming and noise exclusion in imaging Phys. Rev. A (2016).
2. M. Malik, O. S. Magana-Loaiza, and R. W. Boyd, Quantum-secured imaging, Appl. Phys. Lett. 101, 241103 (2012).

Ratio of effort: Exp/Theo/Comp	Exp: 0	%
	Theo: 50	%
	Comp: 50	%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: Computational Physics, Quantum Mechanics

Candidate must have taken and passed well (>=65%) the following courses:

- Quantum Physics and Electromagnetism (year 3)
- Computational Physics (year 2)
- Linear Algebra and Differential Equations (year 2)

Additional comments: The numerical simulations using MATLAB and Mathematica will be essential.

Safety Training Requirements: None

Coherent Perfect Amplification of Light

(1) Prof John Jeffers, (2) Dr Daniel Oi

Project Description:

Absorption and emission of light are governed fundamentally by the rules of both quantum and classical physics. Classical physics provides the optical mode structure and quantum provides the absorption/emission probabilities and hence the light intensities.

In the most striking form of coherent perfect absorption [1] an absorbing medium of subwavelength thickness is rendered transparent or perhaps fully absorbing, merely by changing the mode of the incoming radiation. Precursors to this effect were suggested nearly 20 years ago in quantum optics in a body of work that examined the quantum properties of lossy beam splitters [2-4].

The optical mode structure of amplifying subwavelength films is similar to that of absorbers [5-6]. This project will model such devices and find the spectral and perhaps the quantum properties of the light that they can emit.

The project will begin with a study of the mode structure of slab devices, investigating the thin limit for both attenuating and amplifying media. The output light modes will be calculated and the possibility of basing a laser light source on such structures will be investigated.

Key References:

[1] J. Zhang, K.F. MacDonald and N.I. Zheludev, *Controlling light-with-light without nonlinearity*, Light: Science & Applications (2012) **1**, e18; doi:10.1038/lsa.2012.18, and references therein.
[2] R. Matloob et al., *Electromagnetic Field Quantisation in Absorbing Dielectrics*, Phys. Rev. A **52**, 4823 (1995).
[3] S.M. Barnett et al., *Quantum Optics of Lossy Beam Splitters*, Phys. Rev. A **57**, 2134 (1998).
[4] J. Jeffers, *Interference and the Lossless Lossy Beam Splitter*, J. Mod. Opt. **47**, 1819-1824 (2000).
[5] R. Matloob et al., *Electromagnetic Field Quantisation in Amplifying Dielectrics*, Phys. Rev. A **55**, 1623 (1997).
[6] J. Jeffers et al., *Canonical Quantum Theory of Light Propagation in Amplifying Media*, Optics Communications **131**, 66-71 (1996).

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	50%
Comp:	50%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: High marks in 3rd Year Quantum Physics, Electromagnetism. Computational Physics.

Additional comments: A good level of mathematics will be required. Matlab programming.

Safety Training Requirements . N/A

Using angular momentum of light to detect particles in fluids

(1) Dr Francesco Papoff, (2) Dr Alison Yao, Dr David McKee

Project Description:

Conservation of angular momentum is observed in systems that do not change under rotations; measuring the angular momentum provides very useful information on the nature of the systems investigated. For light beams propagating in a isotropic medium the angular momentum along the direction of propagation is conserved. In this project we are interested in observing violations of the conservation of angular momentum when a beam of light propagates in a fluid that contains small spheres, and in using these violations to probe the density and distribution of the spheres. In the long term, this could lead to effective ways of monitoring the presence of particles in air or water. In this project we will calculate the light scattered by spheres at different positions within a light beam using Mie theory[1] and use the scattered field to evaluate how the change in angular momentum of light depends on the position of the sphere within the light beam. Time permitting, we will then look at the effect of multiple spheres.

Key References:

[1] "The Mie theory [internet resource] : basics and applications ", W Hergert (Wolfram); Thomas Wriedt; Springerlink (Online service), Berlin ; London : Springer 2012

Ratio of effort: Exp/Theo/Comp

Theo:	30%
Comp:	70%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH355 Physics Skills

Additional comments: This project is open to more than one student.

Safety Training Requirements: Laser, chemical, biological, and radiological safety training will be provided.

Computational Modelling of X-ray Free Electron Lasers

(1) Dr Brian McNeil, (2) Dr Gordon Robb

Project Description:

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.

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’. From these, it may be possible to predict new effects that can enhance or extend current XFEL performance.

Key Reference:

[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

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	25%
	Comp:	75%

Suitability: MPhys, BSc, BSc (Maths Physics)

Safety Training Requirements: *Normal office/computer user induction.*

The theory of X-ray Free electron Lasers

(1) Dr Brian McNeil, (2) Dr Gordon Robb

Project Description:

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.

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 Reference:

[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

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	80%
Comp:	20%

Suitability: MPhys BSc, BSc (Maths Physics)
Additional comments:
Safety Training Requirements: *Normal office/computer user induction.*

The scientific applications of X-ray Free Electron Lasers

(1) Dr Brian McNeil, (2) Dr Gordon Robb

Project Description:

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.

Starting from the basic working equations that describe the FEL process, the student will gain an understanding of how an XFEL works and the properties of the light they emit. You will then review the range of basic science that the output from XFELs is being applied to. This covers a wide range from the creation and studies of warm dense matter to the functioning of *in-vivo* organisms and processes. The student will identify the unique features of XFEL output, describe and explain the methods used to apply them in a range of experiments. They will also look forward to future potential application/experiments given an improvement in XFEL output or detection methods. This will require some analysis and numerical calculations to verify their feasibility.

A good student may be able to identify areas where significant advances would have an impact – for example, what if the XFEL were extended into the gamma range of the spectrum? Again, some analysis and numerics may be required to back up any conjectures made.

Key Reference:

[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

Ratio of effort: Exp/Theo/Comp

Exp:	20%
Theo:	50%
Comp:	30%

Suitability: BSc BSc (Phys with Teaching) BSc (Maths Physics)

***For MPhys students the project should be designed to last for two years**

Safety Training Requirements: *Normal office/computer user induction.*

Keeping time with a laser pointer

(1) Jonathan Pritchard, (2) Erling Riis

Project Description:

Absolute time and frequency references underpin key areas of everyday life from telecommunications to navigation using global positioning satellites (GPS). To date, atomic clocks provide the ultimate performance using microwaves or lasers to probe narrow atomic transitions that can provide fractional uncertainties < 10^{-17}, or better than 1s over the lifetime of the universe.

Outside of National Standards Laboratories we require small, portable frequency references offering excellent stability, high reliability and low power consumption. Molecular iodine clocks are a promising candidate for this [1], with a full Atlas of calibrated lines around 532 nm [2] and excellent performance demonstrated [3].

In this experimental project we will explore stabilisation of an off-the-shelf green laser pointer to an atomic reference of an iodine cell to develop a portable, low-cost optical frequency standard. Green laser pointers are diode-pumped solid-state (DPSS) lasers using a diode at 808 nm to pump Nd:YAG which lases at 1064 nm before frequency doubling to 532 nm. Control of the pump current and temperature the laser source will be characterised to tune the laser frequency to perform high-resolution spectroscopy before locking the laser against a narrow iodine line.

Key References:

[1] J. Ye *et al.*, *Molecular Iodine Clock*, Phys. Rev. Lett. **87**, 270801 (2001).

[2] J. Ye *et al.*, *Absolute Frequency Atlas of Molecular I_2 Lines at 532 nm*, IEEE Trans. Instr. Meas. **48**, 544 (1999).

[3] F.-L. Hong *et al.*, *Frequency Comparison of $^{127}I_2$–stabilised Nd:YAG Lasers*, IEEE Trans. Instr. Meas. **48**, 531 (1999).

Ratio of effort: Exp/Theo/Comp

Exp:	70 %
Theo:	20 %
Comp:	10 %

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: We recommend taking PH462 Topics In Quantum Optics and PH455 Topics In Photonics alongside this module.

Additional comments:

Safety Training Requirements:

Classical Analogs of Quantum Coherence

(1) Jonathan Pritchard

Project Description:

A key ingredient of quantum mechanics is the concept of coherence, leading to interference effects as observed for single electrons passing through a double slit or in the population oscillations used for precision atomic clocks following a microwave pulse sequence. When considering the interaction between atoms and light, it can be shown that the optical response of a medium can be derived from a calculation of the off-diagonal coherences, which for a three-level system with two optical fields can be used to switch the medium from absorption to transparency in a phenomenon known as electromagnetically induced transparency.

This quantum coherence can be mapped onto a classical system of coupled oscillators, enabling observation of an analog quantum coherence using either masses on springs or simple electrical circuits [1]. This project seeks to extend this approach to create an electrical circuit model able to simulate the optical response of a single atom in an optical cavity [2] to realise a classical analog model of a quantised system.

The project will compare fully quantum mechanical simulations with a quantum optics toolbox to those of an analog circuit using SPICE, before building working circuits able to experimentally verify the performance of the analog circuit models to create a bench-top simulator of the optical response of an atom coupled to a high finesse optical cavity.

Key References:

[1] C. L. Garrido Alzar at al., *Classical analog of electromagnetically induced transparency*, Am. J. Phys. **70**, 27 (2002)

[2] J. A. Souza *et al.*, *Electromagnetically induced-transparency-related phenomena and their mechanical analogs*, Phys. Rev. A **92**, 023818 (2015)

Ratio of effort: Exp/Theo/Comp

Exp:	33 %
Theo:	33 %
Comp:	33 %

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: We recommend taking PH462 Topics In Quantum Optics alongside this module.

Additional comments:

Safety Training Requirements:

Generating Arbitrary Arrays for Quantum Information Processing

(1) Jonathan Pritchard, (2) Aidan Arnold

Project Description:

Quantum information processing with neutral atoms offers an exciting and scalable platform for performing both digital quantum computation and quantum simulation, with controllable long-range interactions mediated by highly excited Rydberg levels.

A key advantage of neutral atoms is the ability to cool and trap large numbers of qubits, with experiments demonstrating deterministically loaded arrays of arbitrary geometry in both 2D [1] and 3D [2] using holographic traps created with spatial light modulators (SLM's).

Currently, these results have focused on generating red-detuned traps where atoms are formed in the high-intensity focus of a laser beam, which enables efficient algorithms to be used for calculating the phase-mask to apply to the spatial light modulator. This computational project will explore adapting these techniques to generating arbitrary arrays of blue-detuned traps, where now atoms are confined at the intensity minima. This has the advantage of suppressing scattering and shifts caused by the trapping light, as well as enabling trapping of the highly-excited Rydberg states to extend the number of sequential gates that can be performed sequentially for improved performance of neutral atom quantum information processors.

Key References:

[1] Daniel Barredo *et al.*, *An atom-by-atom assembler of defect-free arbitrary two-dimensional atomic arrays*, Science **354**, 1021 (2016)

[2] Daniel Barredo *et al.*, *Synthetic three-dimensional atomic structures assembled atom by atom* (2017), arXiv:1712.02727

Ratio of effort: Exp/Theo/Comp

Exp:	0 %
Theo:	50 %
Comp:	50 %

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: This project is computationally intensive and experience using either Matlab or Python is highly recommended. We recommend taking PH462 Topics In Quantum Optics alongside this module.

Additional comments:

Safety Training Requirements:

Implementation and characterization of optical lattice potentials for ultracold atoms

(1) Dr Elmar Haller, (2) Prof Stefan Kuhr

Project Description:

Experiments with ultracold atomic gases offer unique opportunities to simulate problems of condensed matter physics. In particular atoms in optical lattices potentials, formed by interfering laser beams, can be used to study the motion of quantum mechanical particles in crystal structures. Changing the frequency, polarization and geometrical arrangement of the laser beams, it is possible to simulate a multitude of lattice structures, such as hexagonal, Kagome, and quasi-crystal lattices.

The task of this project is to implement and characterize the lattice potentials with a laser system and CCD cameras in the lab. The implementation includes the design and the construction of the opto-mechanical setup for the lattice beams. The final characterization should provide a detailed mapping of the shape of the lattice potential and a measure for its stability in time. The project is closely connected to another project which provides a computer simulation of interesting new lattice potentials.

Key References:

I. Bloch, "Ultracold quantum gases in optical lattices", Nature Physics 1, 23-30 (2005)

Ratio of effort: Exp/Theo/Comp	Exp:	70 %
	Theo:	30 %
	Comp:	0 %

Suitability: MPhys BSc

Recommended Classes/Pre-requisites: Good knowledge of quantum physics and solid state physics is helpful but not a requirement.

Safety Training Requirements: Contact the project supervisor for further advice

Design and Construction of a Fabry-Perot Scanning Interferometer

(1) Dr Elmar Haller, (2) Prof Stefan Kuhr

Project Description:

TBA See Dr Haller for details

Key References:

TBA

Ratio of effort: Exp/Theo/Comp		
	Exp:	0 %
	Theo:	20 %
	Comp:	80 %

Suitability: MPhys BSc

Recommended Classes/Pre-requisites: TBA.

Safety Training Requirements: Contact the project supervisor for further advice

Magnetic states with long-range interactions

(1) Prof Andrew Daley, (2)

Project Description:

Magnetic phenomena have been explored over many years, and discussions of the transitions to magnetically ordered states (e.g., with Ferromagnetic or Antiferromagnetic ordering in the Ising model) are commonplace in Solid State Physics Classes. Recently, experiments with atoms excited to Rydberg levels with high principle quantum number (>20) have opened new opportunities to look at systems with unusual magnetic interactions – for example, interactions that switch between ferromagnetic and antiferromagnetic as a function of distance between spins. This leads to important open questions regarding what type of order is produced under different conditions, and also how to prepare and measure these types of magnetic order in experiments.

In this project, we will explore the magnetic ordering expected in these unusual long-range Ising models, and develop understanding as to what happens for quantum systems when we also consider transverse Ising models. We will analyse basic properties of models that account for interactions in real experiments, and explore the low-temperature behaviour with analytical and numerical calculations.

A feature of the numerical calculations for longitudinal spin models will be classical monte-carlo calculations based around Markov chains, which make it possible to explore the statistical mechanics of these states.

Key References:

[1] Peter Schauß et al., Nature 491, 87 (2012)
[2] Hendrik Weimer et al., Nature Physics 6, 382 - 388 (2010)
[3] Shannon Whitlock et al 2017 J. Phys. B: At. Mol. Opt. Phys. 50 074001 (2017)

Ratio of effort: Exp/Theo/Comp		
	Exp:	0%
	Theo:	40%
	Comp:	60%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: PH351, PH358

Additional comments: There are separate models that can be studied here, and there are also different numerical approaches for quantum and classical models. This project will involve a mixture of analytical and numerical calculations, and requires a strong background in statistical mechanics. This project may be taken by more than one student.

Safety Training Requirements: None

Quantum transport in superconducting wires and cold atoms

(1) Prof Andrew Daley, (2) Dr Eduardo Mascarenhas, Dr François Damanet

Project Description:

Both in nanoelectronics and in experiments with ultracold atoms, there have been substantial developments over the past few years in the ability to engineer laboratory experiments, so that the quantum mechanical behaviour of electrons and of collections of atoms can be explored in a variety of novel scenarios that bring out a range of surprising and also useful aspects of quantum mechanical motion. In particular, the connection between these experimental platforms has been growing, as experiments with ultracold gases have been developed that mimic the physics of electrons in nanowires. A key milestone was reached with the observation of quantised conductance and transport with interacting particles in a quantum wire in the group of Tilman Esslinger in Zurich [1]. These experiments involved the engineering of optical traps for fermionic ultra-cold atoms: deep traps were produced to represent reservoirs or leads, and were coupled with narrow geometries that represented nanowires.

In this project, we will look at novel transport scenarios which could be explored in such experiments, in order to set a roadmap for future developments also in nanoelectronics. We will particularly explore the dynamics of particles in traps of unusual engineered geometries [2], which allow for so-called topological properties through quantum interference. We will separately investigate the effects of strong interactions on such quantum transport dynamics.

Key References:

[1] "Observation of Quantised conductance in neutral matter", S. Krinner et al., Nature **517**, 64 (2015)
[2] "Quantum Emitters in Two-Dimensional Structured Reservoirs in the Nonperturbative Regime", A. González-Tudela and J. I. Cirac, Physical Review Letters **119**, 143602 (2017)

Ratio of effort: Exp/Theo/Comp	Exp:	%
	Theo:	40%
	Comp:	60%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: PH352, PH359, PH358

Additional comments: There are separate geometries and interaction types that can be studied here, each of which are likely to have markedly different phenomena associated with them. There are also aspects of the project that can be adapted to be more computationally focussed, or more focussed on analytical calculations. As a result, there is room for two students to take on distinct but synergistic aspects of this project, with separate second supervisors. This project requires a mixture of analytical and numerical calculations, and requires a strong background in quantum mechanics and statistical mechanics.

Safety Training Requirements: None

Scattering of light beams carrying angular momentum

(1) Dr Francesco Papoff, (2) Dr Alison Yao

Project Description:

Beams of light with angular momentum have many interesting properties: for instance, when they interact with small particles, their angular momentum can be transfer and the particles rotate, an effect that can be used to create micro and nano engines. To model these beams, one normally uses the paraxial approximation that does not describe properly the relation between the beam's polarization and amplitude. This approximation is good in many cases, but fails when the light beams are tightly focused. Exact solutions of Maxwell's equations that describe exactly light beams have been recently published [1] . In this project we will combine these exact solutions with Mie theory [2] to investigate the scattering of light with angular momentum from micro and nano spheres.

Key References:

[1] "Closed-form bases for the description of monochromatic, strongly focused, electromagnetic fields", N.J. More and M.A. Alonso, Onimous et al., J. Opt. Soc. Am. A, 26, 2211 (2009)
[2] "Lorenz-Mie scattering of focused light via complex focus fields: An analytic treatment", R. Gutiérrez-Cuevas, N. J. Moore, and M. A. Alonso, Phys. Rev. A 97, 053848 (2018)

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	40%
Comp:	60%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Recommended Classes/Pre-requisites: PH355 Physics Skills

Additional comments: This project requires a good understanding of electromagnetism.

Safety Training Requirements: None.

Helical waves in optical cavities for quantum communication

(1) Dr Alison Yao, (2) Prof Gian-Luca Oppo

Project Description:

Quantum optics will play a key role in transforming future applications for secure communications. Quantum cryptography, based on correlations due to quantum entanglement, is the only provably secure form of communication. Maximising the information data rate requires encoding each photon pair with a large amount of information. Helical waves of light carrying orbital angular momentum (OAM), or "twisted light", has received a lot of attention recently due to its capability to boost data rates in optical communication [1]. Using a process known as spontaneous parametric down-conversion (SPDC) it is possible to produce photons that are entangled in their OAM. Although the quantum nature of these photons and their potential for applications in quantum information has been clearly demonstrated [2], SPDC is an inherently inefficient process and thus unlikely to fulfill practical needs. Optical parametric oscillators (OPO) can be used to amplify the entangled signal by several orders of magnitude and by combining knowledge of the quantum properties of the down-converted states [3], and numerical codes developed in the group to model OPOs, this project will investigate the data carrying potential of 'bright' photons entangled in their OAM.

Key References:

[1] J. Wang et al., 'Terabit free-space data transmission employing orbital angular momentum multiplexing', Nature Photonics **6**, 488 (2012)
[2] J. Leach et al., 'Quantum Correlations in Optical Angle–Orbital Angular Momentum Variables', Science **329**, 662 (2010)
[3] A. M. Yao, '*Angular momentum decomposition of entangled photons with an arbitrary pump*', New J. Phys. **13,** 053048 (2011)

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	20%
Comp:	80%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites:

Additional comments: The project requires skills in mathematical and computational techniques.

Safety Training Requirements: Laser, chemical, biological, and radiological safety training will be provided.

Nonlinear Propagation of Fully Structured Light

(1) Dr Alison Yao (2) Dr Duncan McArthur

Project Description:

Laser beams propagating in linear materials diverge during propagation. This diffraction can be compensated for by propagating through nonlinear materials that exhibit an intensity-dependent refractive index. Balancing the divergence and self-focusing results in a beam, known as a spatial soliton, that can propagate without changing shape. However, it is experimentally challenging to achieve this without suffering catastrophic beam collapse. Introducing saturation of the nonlinearity leads to an increase in stability by periodically modulating self-focusing effects first and filamentation later.

Laguerre-Gaussian (LG) modes are ring-like beams with an $\boldsymbol{l}$-fold helical phase structure that carry an orbital angular momentum (OAM). These are of interest due to their potential to carry an increased information content. Unfortunately these are seen to fragment during propagation in a Kerr medium to form $\boldsymbol{2l}$ filaments. Their stability can be increased, however, by using a superposition of LG modes with orthogonal polarisations. The resultant beams are known as fully-structured beams as they have an intensity, phase and polarisation that are spatially structured. The aim of this project is to investigate how this structuring affects the stability of the beams during nonlinear propagation. The result will provide a novel approach to transport high-power light beams in nonlinear media with controllable distortions to their spatial structure and polarization properties.

Key References:

[1] W. J. Firth and D. Skryabin, Phys. Rev. Lett. **79**, 2450 (1997)

[2] F. Bouchard et al., *Polarization Shaping for Control of Nonlinear Propagation*, Phys. Rev. Lett. **117**, 233903 (2016)

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	30%
	Comp:	70%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH352 Quantum Physics & Electromagnetism

Additional comments: This project requires a good level of mathematical ability and preferably some programming experience.

Safety Training Requirements: N/A.

Pattern formation with twisted beams

(1) Dr Alison Yao (2) TBC

Project Description:

In optics, the spontaneous breaking of the translational and rotational symmetries in the plane perpendicular to the direction of light propagation leads to pattern formation in the shape of hexagons, stripes, rhomboids and honeycombs. In this project we study transverse pattern formation for nonlinear crystals in optical cavities under the action of two pump waves [1]. As well as regular patterns, this system is ideal for the generation of rogue waves and optical turbulence [2]. In this project we see how the system is affected by using twisted optical waves (Laguerre-Gaussian modes) as the pump and/or injection.

Key References:

[1] G.-L. Oppo, A. M. Yao and D. Cuozzo, "Self-organization, Pattern Formation, Cavity Solitons and Rogue Waves in Singly Resonant Optical Parametric Oscillators", Phys. Rev. A **88**, 043813 (2013).
[2] C. J. Gibson, A. M. Yao, and G.-L. Oppo, "Optical Rogue Waves in Vortex Turbulence", Phys. Rev. Lett. **116**, 043903 (2016).

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	20%
Comp:	80%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH352 Quantum Physics & Electromagnetism

Additional comments: This project requires a good level of mathematical ability and preferably some programming experience.

Safety Training Requirements: N/A.

Pattern formation with twisted beams

(1) Dr Alison Yao (2) TBC

Project Description:

In optics, the spontaneous breaking of the translational and rotational symmetries in the plane perpendicular to the direction of light propagation leads to pattern formation in the shape of hexagons, stripes, rhomboids and honeycombs. In this project we study transverse pattern formation for nonlinear crystals in optical cavities under the action of two pump waves [1]. As well as regular patterns, this system is ideal for the generation of rogue waves and optical turbulence [2]. In this project we see how the system is affected by using twisted optical waves (Laguerre-Gaussian modes) as the pump and/or injection.

Key References:

[1] G.-L. Oppo, A. M. Yao and D. Cuozzo, "Self-organization, Pattern Formation, Cavity Solitons and Rogue Waves in Singly Resonant Optical Parametric Oscillators", Phys. Rev. A **88**, 043813 (2013).

[2] C. J. Gibson, A. M. Yao, and G.-L. Oppo, "Optical Rogue Waves in Vortex Turbulence", Phys. Rev. Lett. **116**, 043903 (2016).

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	20%
Comp:	80%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH352 Quantum Physics & Electromagnetism

Additional comments: This project requires a good level of mathematical ability and preferably some programming experience.

Safety Training Requirements: N/A.

Scattering of twisted light by chiral molecules

(1) Dr Robert Cameron (2) Dr Alison Yao

Project Description:

The words “chiral” and “chirality” were introduced by Lord Kelvin to describe anything that differs from its mirror image; a human hand is an example of something that is chiral and has chirality. Chirality is particularly important in chemistry and biology, as the molecules that comprise living things are chiral and their chirality is inherent to their behaviour.

Circularly polarised light is often used to study chiral molecules [1]; the interaction between a circularly polarised beam of light and a chiral molecule differs depending on whether the polarisation is left- or right-handed. In this purely theoretical research project you will investigate the scattering of linearly polarised light with helical phase fronts, i.e. light carrying orbital angular momentum (OAM) [2], by a chiral molecule.

There are three objectives:

1. Learn about chiral molecules and light with helical phase fronts.
2. Calculate the relevant scattering rates. This will require you to develop a basic understanding of multipolar expansions, molecular polarisabilities and scattering calculations.
3. Determine whether the scattering rate differs for left- and right-handed helical phase fronts.

Key References:

[1] Laurence D. Barron, *Molecular Light Scattering and Optical Activity* (2004)
[2] Alison M. Yao and Miles J. Padgett, *Adv. Opt. Photon.* **3**, 161–204 (2011)

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	100%
Comp:	0%

Suitability: MPhys, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH352 Quantum Physics & Electromagnetism

Additional comments: This project requires a good knowledge of electromagnetism and a high level of mathematical ability.

Safety Training Requirements: N/A.

Nonlinear Optical Loop Mirrors Based on 3 X 3 fibre optic couplers

(1) Dr N Langford (2) Dr A Yao

Project Description:

The optical fibre is an ideal system for studying non-linear processes such as self-phase and cross-phase modulation because the fibre can guide light over very long distances with low loss [1]. The light in an optical fibre is guided in the core of the fibre and by placing the cores of two fibres close together a fibre coupler can be formed which is the fibre analogue of a beam splitter. The most common form of fibre coupler is the 2 x 2 coupler and if the two output ends of the couplet are joined together it is possible to build the fibre equivalent of a mirror [2]. By exploiting the Kerr optical non-linearity it is possible to make a loop mirror where the strength of the signal reflected by the loop mirror depends on the intensity of the light coupled into the loop mirror [3]. Unlike a bulk optics beam splitter where there are 2 inputs and two output optical fibres offer the potential to make N X N couplers. In this project you will model a non-linear loop mirror using a 3 X 3 fibre coupler and compare the response of this device with that based on a 2 X 2 fibre coupler.

Key References:

[1] Agrawal, Govind (2006). *Nonlinear Fiber Optics* (4th ed.). Academic Press. ISBN 978-0-12-369516-1

[2] D B Mortimore, "Fiber loop reflectors,"*J Lightwave Technol,* vol 6, no 7, pp 1217-1224, July 1988

[3] "N. J. Doran and D. Wood, "Nonlinear-optical loop mirror", Opt. Lett. 13 (1), 56 (1988)

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	10%
Comp:	90%

Suitability: MPhys, BSc, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH 455 Topics in Photonics

Additional comments: This project is available for up to 2 students. Students should be comfortable with programming in MatLab or C.

Safety Training Requirements: Computer workstation.

Astigmatic mirror multipass absorption cells for long path length spectroscopy

(1) Dr N Langford

Project Description:
Optical spectroscopy is a simple way of detecting pollutants in the atmosphere. In most cases the interaction between the absorbing species and the light is described by Beer's Law (I = Ioexp(-aL)) where L is the interaction length and a is the absorption coefficient. In many cases a is small and so to achieve a detectable change in I requires a long interaction length. One way of doing this is to contain the light in a non-resonant optical cavity whereby the mirrors of the cavity are arranged to allow the light to make multiple bounces. This project will involve modelling of the cavity by use of traditional beam tracing methods (ABCD Matrix approach) as well as using Huygens' Integral approach. The modelling will be done using MatLab.

Key References:

1. H. Kogelnik and T. Li, "Laser beams and resonators", Am J. Phys., Vol. 5, No. 10, pp.1550–67 (1966).
2. Kogelnik, H. and Li, T., Laser Beams and Resonators, Applied Optics, Vol. 5, pp. 1551-1552, 1966.
3. McManus, J. B., Kebabian P. L., & Zahniser M. S. Astigmatic mirror multipass absorption cells for long-path-length spectroscopy, Applied Optics, Vol. 33, pp.3336, 1995.
4. Arnaud, J.A. and Kogelnik, H., Gaussian Light Beams with General Astigmatism, Vol. 8, Issue 8, pp. 1687-1693, 1969.

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	10%
Comp:	90%

Suitability: MPhys, BSc Physics, BSc Physics with Teaching, BSc Maths and Physics

Recommended Classes/Pre-requisites: PH 455 Topics in Photonics

Additional comments: This project is available for up to 2 students. Students should be comfortable with programming in MatLab or C.

Safety Training Requirements: Computer workstation.

Characterising Digital Camera Sensors

(1) Dr Daniel Oi

Project Description:

Electro-optic sensors are important components, from photography, machine vision, autonomous vehicle guidance, and scientific data gathering. In this project, the student will characterise the electro-optical performance of a consumer digital camera. Parameters of interest include sensitivity, noise, dark-current, spectral response, and full-well capacity. The student will learn the basic operating principles of CCDs and CMOS imagers and the physics of digital camera sensors.

Key Reference:

Janesick JR. Photon transfer. San Jose: SPIE press; 2007 Aug 14.

Ratio of effort: Exp/Theo/Comp

Exp:	50%
Theo:	20%
Comp:	30%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Pre-requisites: Computational skills, Matlab.

Additional comments:

Safety Training Requirements:

Satellite Quantum Key Distribution

(1) Dr Daniel Oi, (2) Dr Luca Mazzarella

Project Description:

Distributing quantum encryption keys from space will allow secure communication on a global scale. There is considerable international interest in developing missions for the wide-scale deployment of satellite QKD. Strathclyde is working with collaborators both in the UK and overseas to build and fly our own quantum satellites.

A crucial sub-system of SatQKD is the timing and synchronisation of the single photon pulses sent from space to a ground-based optical receiver, especially due to the high relative velocities due to the satellite's orbit. This project would investigate the methods and effectiveness of implementing timing and synchronisation systems required to perform QKD from space.

Key Reference:

Oi DK, Ling A, Vallone G, Villoresi P, Greenland S, Kerr E, Macdonald M, Weinfurter H, Kuiper H, Charbon E, Ursin R. CubeSat quantum communications mission. EPJ Quantum Technology. 2017 Dec 1;4(1):6.

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	50%
Comp:	50%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Pre-requisites: Computational skills, Matlab.

Additional comments:

Safety Training Requirements:

Atom-Cavity Measurement Driven Dynamics

(1) Dr Daniel Oi

Project Description:

Controlling quantum systems is a pre-requisite for quantum technologies, from quantum computation and communication, to enhanced sensing and metrology. Here, we are interested in controlling states of light trapped in a cavity and coupled with an atom. By manipulating and measuring the atom, the cavity field dynamics can be controlled via the entanglement generated by the atom-cavity coupling.

This project will simulate an atom-cavity system and investigate the generation of novel states and the implementation of quantum operations on the cavity field.

Key Reference:

Oi DK, Potoček V, Jeffers J. Nondemolition measurement of the vacuum state or its complement. Physical review letters. 2013 May 23;110(21):210504.

Ratio of effort: Exp/Theo/Comp

Exp:	0%
Theo:	30%
Comp:	70%

Suitability: MPhys, BSc, BSc Maths and Physics, BSc Physics with Teaching

Pre-requisites: Computational skills, Matlab.

Additional comments:

Safety Training Requirements:

Institute of Photonics

Quantum applications of Semiconductor Disk Lasers

(1) Dr Jennifer Hastie, (2) Dr Lucia Caspani

Project Description:

Semiconductor disk lasers (SDLs), thanks to their unique combination of low noise narrow linewidth, wavelength flexibility and high power (see e.g. [1]), are emerging as suitable sources for quantum technology applications. The Institute of Photonics has pioneered the development of these devices and is currently developing high power, narrow linewidth visible SDLs [2] for the strontium optical clock system of our partners within the Quantum Technology Hub for Sensors and Metrology.

The unique features of these lasers can similarly benefit other applications in quantum technologies. In this project, the student will investigate the potential of the SDL systems currently being developed at the Institute of Photonics for the generation of frequency combs and quantum states of light via nonlinear optical processes. The first are fundamental tools for developing ultimate-precision optical clocks, while quantum states of light are fundamental resources for optical quantum information and metrology. Their generation via compact and flexible devices is at the forefront of the research efforts in these fields.

The research will include (but it is not limited to): laser cavity engineering, characterisation of laser dynamics (including intensity noise), design and optimisation of nonlinear optical processes, and quantum states characterisation.

Key References:

[1] S. Calvez, J.E. Hastie, M. Guina, O. Okhotnikov, and M.D. Dawson, "Semiconductor disk lasers for the generation of visible and ultraviolet radiation," Laser & Photonics Reviews 3, 407 (2009).
[2] D. Paboeuf and J.E. Hastie, "Tunable narrow linewidth AlGaInP semiconductor disk laser for Sr atom cooling applications," Appl. Opt. 55, 4980 (2016).

Ratio of effort: Exp/Theo/Comp	Exp:	50%
	Theo:	30%
	Comp:	20%

Suitability: MPhys, BSc

Recommended Classes/Pre-requisites: PH455 Topics In Photonics

Additional comments:

Safety Training Requirements: Laser safety training.

Quantum applications of Semiconductor Disk Lasers

(1) Dr Jennifer Hastie, (2) Dr Paulo Hisao Moriya

Project Description:

Semiconductor disk lasers (SDLs), also referred to as Vertical-External-Cavity Surface-Emitting Lasers (VECSELs), thanks to their unique combination of low noise, narrow linewidth, wavelength flexibility and high power (see e.g. [1]), are emerging as suitable light sources for a wide range of applications. In particular, high performance lasers are fundamental for the development of quantum technologies as it improves atomic samples creation and manipulation which are used as the quantum sensors [2]. This kind of technology is expected to create devices (such as GPS, gravimeters and clocks) which will outperform the existing classical ones [3].

The Institute of Photonics has pioneered the study and development of such laser technology with emission wavelength in different parts of the electromagnetic spectra [1,4]. We are currently developing high power and narrow linewidth visible SDLs [5] for the strontium optical clock system of our partners within the Quantum Technology Hub for Sensors and Metrology.

In this project, the student will investigate the potential of the SDL systems currently being developed at the Institute of Photonics for quantum technologies. For example, the generation of frequency combs and quantum states of light via nonlinear optical processes. The first are fundamental tools for developing ultimate-precision optical clocks, while quantum states of light are fundamental resources for optical quantum information and metrology. Their generation via compact and flexible devices is at the forefront of the research efforts in these fields. The research will include (but it is not limited to): laser cavity engineering, characterisation of laser dynamics (including intensity and frequency noise), design and optimisation of nonlinear optical processes, and quantum states characterisation.

Key References:

[1] S. Calvez, J.E. Hastie, M. Guina, O. Okhotnikov, and M.D. Dawson, "Semiconductor disk lasers for the generation of visible and ultraviolet radiation," Laser & Photonics Reviews 3, 407 (2009).
[2] L. Fallani and A. Kastberg, "Cold atoms: A field enabled by light", Europhysics Letters 110, 5, 53001(7) (2015).
[3] UK National Quantum Technology Hub in Sensors and Metrology: https://www.quantumsensors.org/ .
[4] R. Casula, J.-P. Penttinen, A.J. Kemp, M. Guina and J.E. Hastie, "1.4 µm continuous-wave diamond Raman laser", Optics Express 25, 25, 31377-31383 (2017).
[5] D. Paboeuf and J.E. Hastie, "Tunable narrow linewidth *AlGaInP* semiconductor disk laser for Sr atom cooling applications," Appl. Opt. 55, 4980 (2016).

Ratio of effort: Exp/Theo/Comp	Exp:	50%
	Theo:	30%
	Comp:	20%

Suitability: MPhys and BSc

Recommended Classes/Pre-requisites: PH455 Topics in Photonics

Additional comments: This project is open to more than one student.

Safety Training Requirements: Laser safety training will be provided.

Photonic Neurons: Spiking information processing with lasers

(1) Dr Antonio Hurtado, (2) Prof Thorsten Ackemann

Project Description:

Neuromorphic photonics aims at emulating the brain's powerful computational capabilities for novel paradigms in ultrafast information processing. Biological neurons respond by firing spikes when stimulated. Semiconductor lasers can also produce neuronal dynamical responses similar to those observed in biological neurons but several orders of magnitude faster. This feature makes them ideal candidates for the use in novel neuro-inspired systems for all-optical information processing.

This project will analyse the emulation of different spiking regimes in Semiconductor Lasers (SLs) under the arrival of induced perturbations into the devices. The experimental work will be performed with devices operating at 1310 and 1550nm, the most commonly used wavelengths in optical telecommunication systems, thus making our neuro-inspired photonics platform totally compatible with actual present optical networks. The project will also look at the application of SLs for neuro-inspired information processing tasks such as the development of spiking all-optical logic gates, digital-to-spiking signal format conversion and the propagation of the generated spiking patterns between interconnected SLs.

Key References:

[1] J. Robertson, T. Deng, J. Javaloyes, A. Hurtado**,** "Controlled inhibition of spiking dynamics in VCSELs for neuromorphic photonics: theory and experiments", in Optics Letters, 42, 1560 (2017)
[2] A. Hurtado and J. Javaloyes "Controllable spiking patterns in long-wavelength vertical cavity surface emitting lasers for neuromorphic photonic systems", in Applied Physics Letters, 107, 241103 (2015)
[3] P.R. Prucnal et al, "Recent progress in semiconductor excitable lasers for photonic spike processing", in Advances in Optics and Photonics, 8, 228 (2016)

Ratio of effort: Exp/Theo/Comp

Exp:	70%
Theo:	15%
Comp:	15%

Suitability: MPhys BSc

Additional comments: Basic knowledge in optics and lasers is desirable but not essential. Attendance to PH455 is also recommended.

Safety Training Requirements: Laser safety

Spectroscopy of Dy-doped crystals for mid-IR laser applications

(1) Dr. Vasili Savitski, (2) Prof. Alan Kemp

Project Description:

High-energy narrow-linewidth differential absorption LIDAR (DIAL) systems are widely used for remote gas pollution sensing of industrial and waste disposal sites. These systems are based on laser sources emitting in 3-5 μm spectral range, corresponding to absorption lines of many “greenhouse” gases. Dy doped fluorides and lead halide crystals are characterised with emission in the mid-IR spectral range and absorption bands at the wavelengths suitable for direct diode laser pumping. These features make them attractive for building new diode-pumped laser sources emitting in the wavelength range of 3-5 μm.

In this project systematic spectroscopic study of a range of Dy doped flourides and lead halides in mid-IR will be carried out. Laser related parameters of the crystals (emission cross section, radiative lifetimes, quantum efficiencies, cross-relaxation and upconversion processes) will be evaluated to underpin the efficient laser pumping schemes and oscillation regimes in these crystals.

Key References:

[1] F. Innocenti, R. Robinson, T. Gardiner, A. Finlayson, and A. Connor, "Differential Absorption Lidar (DIAL) Measurements of Landfill Methane Emissions," Remote Sensing 9, 953 (2017).
[2] B. M. Walsh, H. R. Lee, and N. P. Barnes, "Mid infrared lasers for remote sensing applications," Journal of Luminescence 169, 400-405 (2016)

Ratio of effort: Exp/Theo/Comp

Exp:	70%
Theo:	20%
Comp:	10%

Suitability: MPhys, BSc

Recommended Classes/Pre-requisites: PH455 Topics in Photonics

Additional comments:

Safety Training Requirements: Laser safety training required

Photon velocity control on a silicon photonic chip

(1) Dr Michael Strain, (2) Dr Benoit Guilhabert

Project Description:

The vast majority of optical experiments and systems are realised using a few building block components such as beam-splitters, wavelength filters, mirrors and delay lines. Scaling modern experiments on an optical bench requires a huge number of components and critical, stable alignment of each beam path. A solution to the scaling issue has been proposed, using chip-scale optical devices. These mm^2 sized chips contain all of the functionality of standard optical benches at a fraction of the size and with mechanical stability guaranteed by their solid state. Beam splitting, waveguiding, filtering and even non-linear functions have been demonstrated on these chips, but a true optical delay line has not yet been achieved. Delay lines are usually created using a mirror on a movable stage, in essence, increasing the distance photons have to travel. This is not possible on a solid state chip, so other means must be found. Bragg grating devices can slow the velocity of photons travelling in a waveguide using resonant effects. Furthermore, by using electronically tunable Bragg grating devices the photon velocity, and hence on-chip delay time, can be set in an easily accessible manner.

State of the art silicon photonic Bragg grating devices have been fabricated and measured, in the Technology and Innovation Centre. In this project the student will use a custom built software analysis tool to simulate chipscale grating devices and analyse the existing measurement results. This work will show the link between electronic tuning signals and on-chip photon velocity\delay. There is a possibility for publication of this work in a peer-reviewed journal.

Key References:

1. M. J. Strain and M. Sorel, "Design and fabrication of integrated chirped Bragg gratings for on-chip dispersion control," Quantum Electron. IEEE J. **46**, 774–782 (2010).
2. M. J. Strain, M. Gnan, G. Bellanca, R. M. D. La Rue, and M. Sorel, "Retrieval of Bragg Grating Transmission Spectra by Post-process Removal of Spurious Fabry-Perot Oscillations," **17**, 2425–2427 (2009).

Ratio of effort: Exp/Theo/Comp	Exp:	0%
	Theo:	30%
	Comp:	70%

Suitability: MPhys, BSc

Recommended Classes/Pre-requisites:

Additional comments: Some previous experience of Matlab would be desirable.

Safety Training Requirements:

A 6 degree-of-freedom platform for Micro-Transfer Printing on curved surfaces

(1) Dr Michael Strain, (2) Dr Benoit Guilhabert

Project Description:

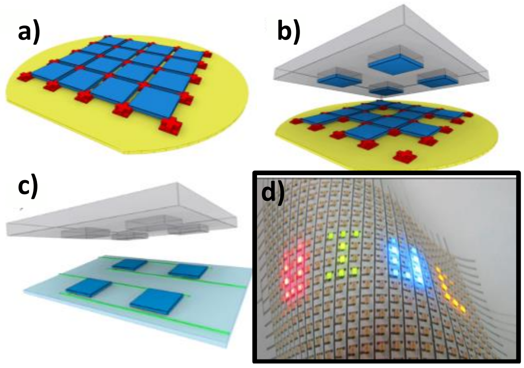

Figure 1: Schematics of the MTP process (a-c). Example of flexible micro-display fabricated by MTP (d).

Micro-Transfer Printing (MTP) allows the precise pick-up, displacement and release of semiconductor devices from their growth substrate to a receiving surface, realising heterogeneous assemblies.[1] The core technology permitting this heterogeneous assembly is a 6 degrees-of-freedom (DOF) positioner based on a nanoscale-accurate linear stage stack. It aligns a printing head to the devices to pick up through a vision system. While nanoscale accuracy MTP of planar devices was demonstrated with such systems, the future of the technique lies with the capability of doing the same on non-flat receiving surfaces such as contact lenses for example. Such a capability will aim to answer the challenges imposed by the emerging augmented reality/near eye micro-displays. To this end, a new stage stack configuration must be explored, namely a Gough-Stewart platform (Hexapod).[2] Many extreme applications use hexapods for steering, such as radio telescope orientation, space docking systems and flight simulators, hence the working principles of such devices are very well known. The project will develop a prototype platform controlled through an Arduino microcontroller and implement a manipulator demonstration. The student will identify the parts to employ for this system in collaboration with the supervisors, design the mechanical parts for the system and will coordinate with the mechanical workshop for their fabrication. Travel and angular ranges considerations will underlay fully this design exercise. The student will assemble the system and implement the Arduino controller in order to achieve 3-dimensional manipulation system. To conclude the project, benchmark and calibration of the system will be carried out along with MTP demonstration.

In this project, the student will gain complementary skills from micro-fabrication to mechanical engineering through computer coding of microcontrollers. PhD students and post-doctoral researchers will support the student within the research group.

Key References:

[1] J. McPhillimy et al., High accuracy transfer printing of single-mode membrane silicon photonic devices, *Opt. Express.*, **26**, 16679- 16688 (2018)
[2] A. Ramírez Gómez, Inertial stabilization system based on a Gough-Stewart parallel platform (2017)

Ratio of effort: Exp/Theo/Comp

Exp:	65%
Theo:	10%
Comp:	25%

Suitability: MPhys, BSc

Recommended Classes/Pre-requisites:

Additional comments:

Safety Training Requirements:

High speed measurement of non-linear processes in silicon nanowire photonics

(1) Dr Michael Strain, (2) Prof Gian-Luca Oppo

Project Description:

Coupled arrays of planar optical waveguides are a useful system for experimentally modelling the behaviour of more difficult to engineer physical systems such as Bose-Einstein condensates. By using non-linear optical materials to create these waveguides, complex intensity dependent effects can also be studied, such as soliton or light bullet formation. Silicon photonics is a well-established material platform for telecommunications systems, and is now finding significant application in quantum optics experiments. Waveguide cross-sections are in the order of 500x220 nanometres allowing the light field to be very strongly confined to an extremely small area. This confinement in turn increases the light-matter interaction, producing strong non-linear effects in both the refractive index and the associated waveguide loss.

Arrays of silicon photonic waveguides with varying amounts of propagation length and coupling between elements in the array have been designed and fabricated. This project will involve the measurement of these optical waveguide arrays in both the linear and non-linear optical regimes. The student will develop skills in the alignment of sub-micron waveguide devices to custom fibre optic components. The waveguide arrays will be imaged using a state of the art near-IR camera to allow characterisation of the distribution of light across the array as a function of input power. These results will give an insight into the interaction of light travelling in coupled systems and how it can be controlled using the input signal intensity.

The student will develop experience of automated laboratory systems using LabView control, fibre optics based measurement systems and silicon photonic device measurements. The project will also involve the post-processing of image data using Matlab. This work will detail the limits of current state-of-the-art silicon photonics as a tool for quantum and non-linear optics. The student will produce data sets to compare with theoretical models.

Key References:

[1] Q. Lin, O. J. Painter, and G. P. Agrawal, “Nonlinear optical phenomena in silicon waveguides: modeling and applications.,” Opt. Express, vol. 15, no. 25, pp. 16604–44, Dec. 2007.
[2] J. Leuthold, C. Koos, & W. Freude, *“Nonlinear silicon photonics,”* Nature Photonics, 4(8), 535–544, 2010.
[3] Y. Lahini, A. Avidan, F. Pozzi, M. Sorel, R. Morandotti, D. N. Christodoulides, and Y. Silberberg, “Anderson localization and nonlinearity in one-dimensional disordered photonic lattices,” *Phys. Rev. Lett.* 100, 1 (2008).

Ratio of effort: Exp/Theo/Comp

Exp:	70%
Theo:	10%
Comp:	20%

Suitability: MPhys, BSc

Recommended Classes/Pre-requisites:

Additional comments: Some previous experience of Matlab would be beneficial but not essential.

Safety Training Requirements: Laser safety course