Programme and Abstract Book

45th IOP Plasma Physics Conference

9–12 April 2018
Queens University Belfast, Belfast, UK

Organised by the IOP Plasma Physics Group
## Programme Overview

### Monday 9 April

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<tr>
<td>11:00</td>
<td>Registration</td>
<td>Peter Froggatt Centre, QUB</td>
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<tr>
<td>12:00</td>
<td>Lunch</td>
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<tr>
<td>13:00</td>
<td>Welcome and talks (1 Invited and 1 Contributed)</td>
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<tr>
<td>14:10</td>
<td>Culham Thesis Prize Talk</td>
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<td>14:50</td>
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<td>16:50</td>
<td>Poster Introductions</td>
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<tr>
<td>17:10</td>
<td>Posters, exhibition and refreshments</td>
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<tr>
<td>19:00</td>
<td>Welcome reception</td>
<td>Great Hall, QUB</td>
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### Tuesday 10 April

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<tr>
<td>09:00</td>
<td>Talks (2 Invited and 1 Contributed)</td>
<td>Peter Froggatt Centre, QUB</td>
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<td>Refreshment break</td>
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<td>11:00</td>
<td>Talks (1 Invited and 3 Contributed)</td>
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<td>12:40</td>
<td>Lunch</td>
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<td>13:40</td>
<td>Excursion to Titanic Museum</td>
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<tr>
<td>19:00</td>
<td>Evening Outreach Event</td>
<td>Peter Froggatt Centre, QUB</td>
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### Wednesday 11 April

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<td>10:20</td>
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<td>10:40</td>
<td>Talks (1 Invited and 2 Contributed)</td>
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<td>12:00</td>
<td>IOP Plasma Group AGM*</td>
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<td>Talks (2 Contributed)</td>
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<td>16:10</td>
<td>Poster Introductions</td>
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<tr>
<td>16:30</td>
<td>Poster session and refreshments</td>
<td>Belfast City Hall</td>
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<td>19:00</td>
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<td>19:30</td>
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<td>Belfast City Hall</td>
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Programme

Monday 9 April

11:00   Registration
12:00   Lunch
13:00   Welcome
13:10   (Invited) Micro-instabilities near the edge of tokamak plasmas
        David Dickinson, University of York, UK
13:50   The role of coherent, sub 600fs, contrast in harmonic generation from overdense plasmas
        Hannah Donnelly, Queen’s University Belfast, Northern Ireland
14:10   (Culham Thesis Prize Talk) Investigations of ion acceleration from solid targets driven by ultrashort laser pulses
        Clare Scullion, Queen’s University Belfast, Northern Ireland
14:50   Refreshment break
15:10   (Invited) Nitrogen fixation as a plasma application
        Miles Turner, Dublin City University, UK
15:50   Study of the Hole-cyclotron instability in semiconductor quantum magneto plasmas
        Fatima Areeb, Government College University, Pakistan
16:10   The study of fuzzy tungsten production in a magnetron source
        Patrick McCarthy, University of Liverpool, UK
16:30   (Rutherford Prize Talk) Winner to be announced
16:50   Poster Introductions
17:10   Posters and refreshments
19:00   Welcome Reception
Tuesday 10 April

09:00  
(Invited) **Global simulations of the solar wind magnetosphere interaction**
Jonathan Eastwood, Imperial College London, UK

09:40  
**Time-resolved characterisation of the evolution of electrostatic collisionless shocks**
Thomas Hodge, Queen’s University Belfast, Northern Ireland

10:00  
(Invited) **Plasma-driven space radiation replication and radiation hardness assurance**
Bernhard Hidding, University of Strathclyde, UK

10:40  
**Refreshment break**

11:00  
(Invited) **Investigating the origins of magnetic fields using the National Ignition Facility**
Jena Meineke, University of Oxford, UK

11:40  
**MAST upgrade status and plans for first plasma**
Richard Martin, Culham Centre for Fusion Energy, UK

12:00  
**Comparative study of ‘COST Reference Microplasma Jets’**
Frederik Riedel, University of York, UK

12:20  
**Two-dimensional Vlasov simulations of parametric wave decay and stochastic electron heating**
David Speirs, University of Strathclyde, UK

12:40  
**Lunch**

13:40  
**Excursion to Titanic Museum**

19:00  
**Outreach Lecture**
Deborah O’Connell and Norman Maitland, University of York, UK
Wednesday 11 April

09:00  Guiding laser-produced fast electrons using large magnetic fields
       Kate Lancaster, University of York, UK

09:40  Monitoring of atomic layer deposition processes using remote plasma optical emission spectroscopy
       Joe Brindley, Genco Ltd, UK

10:00  Local gyrokinetic simulations of tokamak pedestals investigating how magnetic shear affects kinetic ballooning modes
       Stephen Biggs, University of York, UK

10:20  Refreshment break

10:40  New frontier science experiments campaign on DIII-D Tokamak launched in 2017
       Mark Koepke, West Virginia University, USA

11:20  Wake potential in relativistic quantum plasma
       Arroj Ahmad Khan, COMSATS Institute of Information Technology Lahore, Pakistan

11:40  HALO - A full orbit code for calculation of the growth and saturation of Alfven eigenmodes
       James Buchanan, Culham Centre for Fusion Energy, UK

12:00  IOP Plasma Group AGM

12:30  Lunch

13:30  Generation and transport of reactive species in a Surface Barrier Discharge
       Mohammad Hasan, University of Liverpool, UK

14:10  Magnetic interaction of adjacent laser wakefields in an inhomogeneous plasma
       Feiyu Li, University of Strathclyde, UK

14:30  Spatio-temporal plasma heating mechanisms in a radio-frequency electrothermal microthruster
       Scott Doyle, University of York, UK

14:50  Lethal and sub-lethal effects of laser accelerated protons for radiotherapy applications
       Pankaj Chaudhary, Queen's University Belfast, Northern Ireland

15:10  Refreshment break

15:30  Experimental demonstration of a sub-terahertz extended interaction oscillator driven by a pseudospark-sourced sheet electron beam
       Adrian Cross, University of Strathclyde, UK

15:50  Prediction and analysis of the transition to the avalanching and quasilinear regimes of kinetic resonant modes in tokamak plasmas
       Benjamin Woods, University of York, UK

16:10  Poster Introductions

16:30  Poster Session Two and refreshments

19:00  Reception at Belfast City Hall

19:30  Conference Dinner at Belfast City Hall
Thursday 12 April

09:00  [(Invited) Synthetic divertor diagnostics for integrated data analysis at MAST-U with ray-tracing]
Matthew Carr, Culham Centre for Fusion Energy, UK

09:40  Out-of-band extreme ultraviolet emission from a droplet-based laser-produced Sn plasma source
Francesco Torretti, ARCNL, Netherlands

10:00  Optical imaging spectroscopy of magnetised plasmas
Paul Bryant, University of Liverpool, UK

10:20  Deposition removal from fusion optics
David Shaw, University of York, UK

10:40  Refreshment break

11:00  Envelope solitons in collisional superthermal plasmas: the role of dissipation and suprathermal particles
Sharmin Sultana, Queen’s University Belfast, Northern Ireland

11:20  TOF-based diagnostics system for high-energy laser-accelerated proton beams
Giuliana Milluzzo, Queen’s University Belfast, Northern Ireland

11:40  Characterisation of the plasma filled rod pinch diode operation
James Macdonald, Imperial College London, UK

12:00  [(Invited) Tailoring intense laser fields for the generation of bright XUV pulses from plasmas]
Mark Yeung, Queen’s University Belfast, Northern Ireland

12:40  Lunch and close
Poster Programme

P1  Withdrawn

P2  XUV absorption in warm dense aluminium
Cormac Hyland, Queen’s University Belfast, Northern Ireland

P3  Impact of plasma physics and engineering constraints on a fusion neutron source for a transmutation system
Bong Guen Hong, Chonbuk National University, South Korea

P4  Withdrawn

P5  Phase mixing of large amplitude relativistic electron plasma oscillation with inhomogeneous ion background
Mithun Karmakar, Saha Institute of Nuclear Physics, India

P6  CCP-Plasma and Plasma-HEC: UK funded networks for computational plasma physics and high-end computing
Tony Arber, University of Warwick, UK

P7  K-edge shift under warm dense matter conditions
David Bailie, Queen’s University Belfast, Northern Ireland

P8  Ultrafast dynamics of liquid water irradiated by picosecond proton pulses
Nicole Breslin, Queen’s University Belfast, Northern Ireland

P9  Characterisation of atmospheric pressure plasmas
Rachael Irwin, Queen’s University Belfast, Northern Ireland

P10  Study of Ar Photo-ionisation Physics using VULCAN
Rachael Irwin, Queen’s University Belfast, Northern Ireland

P11  High flux table-top synchotron radiation from a compact plasma waveguide
Jian Wang, University of Strathclyde, UK

P12  In search of line coincidence photopumping
Lauren Hobbs, AWE, UK

P13  Pure proton beams accelerated by the interaction of intense laser pulses with thin cryogenic hydrogen ribbons
Philip Martin, Queen’s University Belfast, Northern Ireland

P14  Withdrawn

P15  On the effect of plasma composition and highly energetic electrons on plasma expansion
Ibrahem Elkamash, Queen’s University Belfast, Northern Ireland

P16  Multiscale simulations of Langmuir turbulence excited during ionospheric radio heating experiments
Timothy Heelis, University of Strathclyde, UK

P17  Novel approach to laser-driven multi-stage ion acceleration
Simon Ferguson, Queen’s University Belfast, Northern Ireland
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<td>Kathryn Polin, Queen’s University Belfast, Northern Ireland</td>
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<td>P19</td>
<td>Commissioning and initial experiments of an EUV capillary discharge laser</td>
<td>Sarah Wilson, University of York, UK</td>
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<td>Proton array focused by a laser-irradiated mesh</td>
<td>Shuhua Zhai, Queen’s University Belfast, Northern Ireland</td>
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<td>P21</td>
<td>Gas phase discharges inside electrolyte solutions: Plasma imaging, kinetics and simulations</td>
<td>Leonidas Asimakoulas, Queen’s University Belfast, Northern Ireland</td>
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<td>P23</td>
<td>Capillary Z-pinch plasma generated by impulse transformer</td>
<td>Balazs Fekete, University of Pecs, Hungary</td>
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<td>P24</td>
<td>Waveguide properties of the capillary Z-pinch plasma</td>
<td>Anatoliy Shapolov, University of Pecs, Hungary</td>
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<td>Effect of current diffusion on the inter-ELM pedestal evolution in JET-ILW type I ELMy H-mode plasmas</td>
<td>Laszlo Horvath, University of York, UK</td>
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<td>P26</td>
<td>An experimental concept for investigating non-linear microwave interactions in magnetised plasma</td>
<td>Kevin Ronald, University of Strathclyde, UK</td>
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<td>Pre-clinical evaluation of lethal and sub-lethal DNA damage in cells cultures by ultra-short pulse and ultra-high dose rate laser accelerated protons</td>
<td>Carla Maiorino, Queen’s University Belfast, Northern Ireland</td>
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<td>P28</td>
<td>Tracking dust in magnum-PSI</td>
<td>Luke Simons, Imperial College London, UK</td>
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<td>Electrostatic shock to pulse transition in multispecies plasmas</td>
<td>Ibrahim Elkamash, Queen’s University Belfast, Northern Ireland</td>
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<td>Temporal evolution of high Mach number electrostatic shocks in Laboratory plasma</td>
<td>Hamad Ahmed, Queen’s University Belfast, Northern Ireland</td>
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<td>P31</td>
<td>Carbon ion acceleration from nanometre-thick foils utilising ultra-short laser pulses</td>
<td>Aodhan McIlvenny, Queen’s University Belfast, Northern Ireland</td>
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<td>P32</td>
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<td>P33</td>
<td>Inductive compression and heating of a laser produced plasma</td>
<td>James G Lunney, Trinity College Dublin, UK</td>
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<td>P35</td>
<td>Insights into reactive species delivery and scaling using plasmas produced in high aspect ratio needles</td>
<td>Andrew Gibson, University of York, UK</td>
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<td>P36</td>
<td>Monitoring and control of plasma based atomic layer processes</td>
<td>Kari Niemi, University of York, UK</td>
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P37  Withdrawn

P38  Plasma enhanced-pulsed laser deposition: proof-of-concept
David Meehan, University of York, UK

P39  Investigation of zonal flow stability using spatial averaging
Sanket Gadgil, University of Warwick, UK

P40  Observing dynamics of electron solvation in H2O during ultrafast pulsed-ion radiolysis
Mark Coughlan, Queen’s University Belfast, Northern Ireland

P41  Relativistic electron beam effects on the hole acoustic instability in degenerate semiconductor plasmas
Muhammad Siddique, University Faisalabad, Pakistan

P42  Theoretical issues in modelling ion cyclotron emission associated with transient events in magnetically confined plasmas
Bernard Reman, University of Warwick, UK

P43  Effect of exchange correlation potential on dispersion properties of lower hybrid wave in relativistic degenerate plasma
Prerana Sharma, Ujjain Engineering College, India

P44  Observations of supercontinuum generation in water with a nanosecond Nd:YAG laser
William Graham, Queen’s University Belfast, Northern Ireland

P45  Non-linear dynamics of quantum plasmas: hydrodynamic pressure tensors with kinetic behaviour
Dragos Palade, National Institute for Laser, Plasma and Radiation Physics, Romania

P46  Assessing the impact of 3D eddy currents on merging compression start-up in ST40
Jonathan Wood, Tokamak Energy Ltd, UK

#IOPplasma2018
Micro-instabilities near the edge of tokamak plasmas

D Dickinson
University of York, UK

Small scale plasma instabilities in magnetic confinement fusion devices are driven by gradients in equilibrium quantities such as the density and temperature. These microinstabilities can lead to the turbulent transport of heat and particles down the gradient, thereby limiting the achievable gradients and hence fusion performance. In this talk we will use specific case studies from JET and MAST to explore the role such microinstabilities may play near the edge of tokamak plasmas.

In the high performance “H-mode” operation of tokamaks the gradients of temperature and density are seen to increase significantly near the plasma edge in a region known as the pedestal; an indication that the underlying microinstability behaviour has changed. This leads to much larger core pressure and therefore greatly improved fusion performance, making H-mode an attractive operating regime. However, as well as improved performance, H-mode operation often results in quasi-periodic large scale instabilities localised in the plasma edge, known as ELMs. These ELMs result in the ejection of filaments from the confined plasma carrying significant energy, causing the collapse of the pedestal and posing a potential risk to the surrounding vessel components. The potential risk and reward of operating with a pedestal has meant that this has been an area of significant research effort helping to improve our understanding of the physics involved and our ability to make predictions. There are, however, a number of outstanding issues to address.

The performance benefit of operating with a pedestal depends upon the pedestal height and width, known as the pedestal structure. In order to be able to predict the overall performance we therefore need to be able to predict this structure. Theoretical work suggests that large scale ELMs are coupled peeling-ballooning (PB) modes, and this is consistent with experimental observations in a wide range of cases. For the PB to be unstable the pedestal must be sufficiently wide. The gradients found in the pedestal are typically quite close to those at which the kinetic ballooning instability (KBM) becomes unstable. The EPED model combines the stability limits for the PB and KBM to produce a prediction for the pedestal structure just before an ELM event. This has been successfully tested across a very large range of parameter space, typically giving agreement with observations within 20%, as shown in figure 1. Despite this success, it is known that important physical effects are not captured by EPED and experimentally observed trends are not always recovered, raising concerns for the ability to apply EPED for future devices. Further, EPED only strictly provides predictions for the structure at the ELM onset – future reactors will need to avoid triggering ELMs so also we need to understand how the pedestal evolves in the period between ELMs.

Here we will use case studies from MAST and JET with a focus on computational microinstability analysis in and around the pedestal. Limitations of the models underlying these simulations will be discussed and the consequences for predictive models will be explored. It is important that we have a range of theoretical tools to study the pedestal, from first-principles modelling of the turbulent transport through to reduced predictive models, and that these are tested against experiment.
The role of coherent, sub 600fs, contrast in harmonic generation from overdense plasmas

H Donnelly, M Yeung, J Bierbach, M Coughlan, B Dromey and M Zepf

Queen’s University Belfast, Northern Ireland, Friedrich-Schiller-Universität, Germany

Ultrashort extreme ultraviolet pulses generated from intense laser matter interactions, form an area of research at the very forefront of laser physics. With promising applications such as attosecond laser physics and the seeding of free electron X-ray lasers, this area of research is set to provide us with new insight into many areas of physics.

This presentation looks at harmonic data analysed from an experiment undertaken on the JETI 40 Laser in Jena Germany. Due to the laser intensity the main harmonic generation method is the relativistic oscillating mirror (ROM). The initially solid target is irradiated with an ultrashort, relativistically intense ($\alpha_o > 1$) laser pulse causing the surface of the target to oscillate relativistically. This surface is then reflective to the incident laser light which is periodically upshifted resulting in a non-sinusoidal reflected wave consisting of high harmonics.

It has been well studied how the laser contrast on the picosecond timescale effects the efficiency of the harmonics produced however for the first time we examine the effect of the near time contrast (<600fs). By changing the third order dispersion (TOD) of the incident pulse as well as controlling an introduced prepulse we are able to have greater control over the plasma conditions and therefore the harmonics produced.

The picture becomes complicated and it appears that different harmonic orders have different optimum TOD settings. The need for greater control over the plasma conditions will become more important as we move towards shorter and shorter pulse durations where the plasma has to be optimum at that exact time. By optimising as many parameters as possible we will be able to move towards efficient enough XUV sources needed for the applications above.


(Culham Thesis Prize Talk) Investigations of ion acceleration from solid targets driven by ultrashort laser pulses


Queen’s University Belfast, UK, École Polytechnique, France, Istituto Nazionale di Ottica, Italy, Institute of Basic Science (IBS), South Korea, Gwangju Institute of Science and Technology (GIST), South Korea, Imperial College London, UK, University of Strathclyde, UK, Rutherford Appleton Laboratory, UK, Università di Pisa, Italy, Helmholtz Institute Jena, Germany

High power lasers offer a compact and cost-effective method for accelerating ions with promising characteristics for widespread applications in industry, healthcare and science. This work details experimental and supporting numerical and diagnostic development work related to the acceleration of ions by ultra-high power laser pulses. Research in this broad area has been ongoing for over a decade, with continual progress in delivering high laser intensities on target, creating new target types, and improving diagnostic systems. The work presented was carried out to further understand the underlying mechanisms which take place when thin solid targets are irradiated under different conditions. The key acceleration mechanisms discussed are the well established target normal sheath acceleration (TNSA), radiation pressure acceleration (RPA) and transparency enhanced acceleration (TEA).
The acceleration of ions generated by the irradiation of thin solid targets by ultrashort linearly polarised (LP) and circularly polarised (CP) laser pulses has been investigated. The interactions of high intensity, ultrashort laser pulses with ultrathin carbon foils (2.5 - 100 nm) whilst employing a double plasma mirror configuration were carried out on the Gemini facility at the Central Laser Facility, UK(3). Flat foil aluminium targets were irradiated at the PULSER laser at the Gwangju Institute of Science and Technology using LP laser pulses and no plasma mirrors. The key diagnostics employed were Thomson parabola spectrometers (TPS), radiochromic film (RCF) and Columbia Resin #39 (CR-39). Significant work was undertaken to calibrate these diagnostics to give information about the quantity, energy and type of ions produced in addition to their spatial profile(4).

For the thicker targets, the maximum ion energies were higher for LP pulses, while below 25 nm there were significantly higher energies for both protons (35 MeV) and carbon ions (25 MeV/nucleon) for CP laser pulses. A strong difference in the beam profile was observed for the different polarisations, and 3D PIC simulations are in good agreement with the measurements, providing evidence that a regime in which RPA is the dominant acceleration mechanism can be accessed at current intensities by careful control of the interaction parameters such as the pulse contrast, polarisation and target thickness(3).


(Invited) Nitrogen fixation as a plasma application
Miles Tumer
Dublin City University, UK

Study of the Hole-cyclotron instability in semiconductor quantum magneto plasmas
F Areeb1,2, A Rasheed1, M Jamil1, M Siddique1 and P Sumera1
1Government College University, Pakistan, 2Queens University Belfast, Northern Ireland

By an externally injected electron beam the excitation of electrostatic hole-cyclotron waves generated in semiconductor plasmas is examined using a quantum hydrodynamic model. Tunneling potential, Fermi degenerate pressure, and exchange-correlation potential are the quantum effects that are considered. The growth rate of the wave is analyzed on varying the parameters normalized by hole-plasma frequency, like the angle $\phi$ between propagation vector and applied magnetic field $B_0$, speed of the externally injected electron beam $v_0$ and angle $\theta$, the thermal temperature of the electron beam, external magnetic field $B_0$, that modifies the hole-cyclotron frequency, and finally, the semiconductor electron number density.

The QHD model is used to calculate the velocities and number densities of the electrons and holes of the semiconductor plasma.
This study provides the sound applications of low frequency electrostatic cyclotron waves in nano-sized semiconductor devices, where such a mode may appear as signal noise. Moreover, the graphical analysis of hole-cyclotron modes signifies that the gyratory oscillations of semiconductor holes enhance the electrostatic field oscillations in semiconductor quantum plasmas.

The study of fuzzy tungsten production in a magnetron source

P McCarthy and J Bradley
University of Liverpool, UK

Nanostructured W has been studied comprehensively through experiments due to the strong likelihood of W being included as a plasma facing material in future fusion reactors, most notably ITER and DEMO. The nanostructure, more often called fuzz, is produced when He ions of a sufficient energy irradiate a W surface and high pressure He bubbles are formed, with loop punching and W adatom processes being theorised to produce the tendril structure [1]–[3]. The accepted values for the conditions required to produce W fuzz formation have been summarised [4], [5] and generally for surface temperatures of between 1000K to 2000K, a He ion energy of ≥ 20eV and a fluence of He ions of at least 2.4 x 10^{24} m^{-2} W fuzz can be formed. Recently the importance of looking at lower flux devices has become more prevalent, particularly the use of magnetron sputtering devices to investigate He irradiation of W for fusion applications [6]. The devices themselves allow sputtering of a known metal target due to confinement of plasma in front of the target, with energetic plasma ions bombarding the target surface and producing sputtered atoms which are deposited on a substrate. In this work this effect is used for insights into deposition of metal atoms on to a W surface which will be transitioning to fuzz, and what the overall effect on the fuzz structure is in these deposition environments. Previous studies have focussed on low fluence ranges in magnetrons (∼10^{24} m^{-2}) [6] but here we look at higher fluence (>10^{24} m^{-2}), deposition regimes. The ion energy is varied from the non-sputtering regime (≤100eV) to the sputtering regime of He on W (≥100eV). The surface structures produced from these investigations will be analysed using SEM and FIB-SEM for thickness data, and EDX analysis for the chemical composition of the structures.


(Rutherford Prize Talk) **Winner to be announced**
Global simulations of the solar wind magnetosphere interaction

J Eastwood, J C Chittenden, L Mejnertsen, R Desai and J Eggington

Imperial College London, UK

Global simulations of the interaction between the magnetised solar wind plasma and the Earth’s magnetosphere are crucial for placing satellite observations in the proper context and for providing a better understanding of magnetospheric structure and dynamics under all possible input conditions. Furthermore, magnetospheric simulations are a key component in efforts to predict space weather. The magnetosphere occupies a large volume relative to typical plasma scale lengths and so fluid codes are typically used to model its behaviour.

Here we describe new work at Imperial College London developing global simulations of the solar wind–magnetosphere interaction. This work is based on the Gorgon MHD code developed in the Plasma Physics group at Imperial, which has been used to successfully model a variety of different laboratory plasma devices such as wire array Z-pinches and inertial confinement fusion experiments. The code uses a unique explicit formalism which enables efficient parallel scaling, and employs other numerical techniques and approaches that are different from other codes used to perform similar modelling, but which may provide important capability.

We review recent results showing how the precession of the planetary dipole when it is offset from the planetary rotation axis changes the structure of the magnetosphere. We focus on the case of Neptune, whose magnetosphere was encountered by Voyager 2 and was found to have a highly offset dipole, representing a significant modelling challenge. Other results concerning the effects of variable solar wind flow and the modelling of magnetosphere-ionosphere coupling will be highlighted. We will also discuss a new activity modelling the radiation belts using particle codes coupled to the magnetospheric fields.

Finally, we will conclude by describing two UK space weather consortia funded by NERC (‘Rad-Sat’ and ‘SWIGS’), where this simulation work is being used for modelling radiation belt dynamics and ground induced currents.

Time-resolved characterisation of the evolution of electrostatic collisionless shocks

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Collisionless shock waves (CSW) arise in plasma when an abrupt change in plasma conditions is not caused by binary collisions but the collective behaviour of the plasma. CSW are thought to be highly common in astrophysical environments due to the low ambient density. It is thought that shocks caused by supernova remnants expanding into the interstellar medium accelerate particles that are responsible for cosmic rays measured high in the Earth’s atmosphere. CSW can also be found in our solar system as planetary bow shocks and interplanetary shocks \cite{1,2,3}.

Intense laser-plasma interactions provide a way to launch CSW in conditions relevant to astrophysical plasmas. The interaction of an intense laser pulse with a solid target produces dense plasma, which flows with high velocity, into an ambient background medium. CSW are generated by the sudden expansion of this dense plasma into a tenuous ionized background.

Previous studies by the group \cite{4} have determined initial conditions required to create shocks and characterized their formation and initial evolution. We have now extended this to follow the evolution of the shock over a longer temporal window.
Shocks are observed by using a laser accelerated proton beam as a charged particle probe for radiography. This allows simultaneous measurement of the spatial profile, electric field distribution and shock front propagation velocity over a relatively large temporal window, with high temporal and spatial resolution.

We present results obtained using the VULCAN laser at the Rutherford Appleton Laboratory showing development and evolution of a pair of shocks from a compressed plasma shell and comment on the evolution of the electric field and the associated potential.

(Invited) **Plasma-driven space radiation replication and radiation hardness assurance**

**B Hidding**

University of Strathclyde, UK

Plasmas, driven either by intense laser pulses or particle beams, can accelerate various types of particles such as electrons, protons and ions to relativistic energies on cm-scale distances. The particle beam output from such plasmas is typically very broadband. This makes them potentially ideal candidates to reproduce various kinds of radiation in space, which is similarly broadband, with high spectral accuracy. Such space radiation, in turn, is a substantial threat to electronics and biosystems onboard of space vessels. Radiation hardness assurance (RHA) is therefore required on the component and system level for any space mission. Plasma-based space radiation production and RHA is developed as a collaboration of SCAPA, the Scottish Centre for the Application of Plasma-based Accelerators and CLF, the Central Laser Facility in the UK, European Space Agency and other stakeholders. This presentation will cover the fundamentals, challenges and prospects of this approach [2].


https://www.nature.com/articles/srep42354

(Invited) **Investigating the origins of magnetic fields using the National Ignition Facility**

**J Meineke**

University of Oxford, UK

Radio-synchrotron emission and Faraday Rotation measurements have all revealed that the universe is ubiquitously magnetised—from clusters to filaments to voids—implying that magnetic fields are essential players in the dynamics of luminous matter. The standard model for the origin of galactic and intergalactic magnetic fields is through the generation of small seed fields and amplification of these fields via turbulent motions or dynamo. Due to the invariance of magnetohydrodynamic equations, high-powered lasers can recreate scaled astrophysical events. Previous experiments have demonstrated the generation of seed fields by the Biermann battery mechanism in laser-produced shock waves and the development of Kolmogorov turbulence, as seen in the Coma cluster, that demonstrated amplification of magnetic fields, analogous to supernova remnant Cassiopeia A. Additionally, recent experiments conducted using the Omega laser at the Laboratory for Laser Energetics (LLE) generated low Prandtl number (Pm = Rm/Re) turbulent dynamo.

We present experimental efforts underway at the National Ignition Facility (NIF) to generate high Prandtl number turbulent dynamo relevant to galaxy clusters where generated magnetic energy reaches equipartition with kinetic energy. Using 0.3 MJ of the NIF laser, two laser-produced plasmas passed through non-conducting grids to generate turbulence before undergoing a head-on collision where turbulent dynamo could be generated. Preliminary analysis indicates the first laboratory measurements of high-Prandtl number (Pm>1) turbulent dynamo
in a laser-produced plasma to explain the ubiquitous magnetisation of the universe. Furthermore, proton radiography indicates generated magnetic fields >2MG resulting in a mean free path larger than the Larmor radius, resulting in suppression of heat conduction and magnetised electrons.

**MAST upgrade status and plans for first plasma**

R Martin and the MAST Upgrade Team

Culham Centre for Fusion Energy, UK

The MAST Upgrade tokamak will start operating in 2018 with a uniquely flexible divertor to explore power exhaust, one of the key issues facing the development of fusion as an energy source and accessing improved confinement through a combination of strong plasma shaping and tailoring the energetic particle distribution generated by neutral beam injection. An extensive array of highly resolved diagnostics of the core plasma and divertors will make MAST Upgrade an excellent facility for detailed physics studies to better understand fusion plasmas through experiments and comparisons with theory and modelling.

The construction of MAST Upgrade is nearing completion, with the interior of the machine now fully assembled, with the layout shown in the figure below. This includes the installation of 19 poloidal field coils, a new central solenoid, two tightly baffled divertor cassettes, on and off axis neutral beam injectors and diagnostics housed within the vacuum vessel. An extensive array of magnetics sensors for equilibrium reconstruction, analysis of MHD activity, plasma control, and characterisation of halo currents have been installed, together with 850 Langmuir probes for characterising the plasma in contact with the graphite tiles in the divertors and 64 channels of foil bolometry to measure the distribution of radiation losses across the device.

The first physics campaign will use the new capabilities of MAST Upgrade to explore the effects of tailoring the magnetic field in the divertors to maximise radiation losses from the plasma and reduce the divertor heat loads. Operation of the on and off axis neutral beams will be optimised to reduce the redistribution of energetic particles due to instabilities excited by gradients in the fast ion density profile, and to tailor the q profile to minimise MHD instabilities. The effect of the divertor configuration and neutral gas pressure in the main chamber on access to the high confinement, Hmode, regime will be explored to maximise the pedestal height, thereby improving the performance of the core plasma.

Plans for the completion of MAST Upgrade and associated infrastructure will be presented, and preparations for achieving the first plasma.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053 and from the RCUK Energy Programme [grant number EP/I501045]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ccfe.ac.uk*. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
Comparative study of 'COST Reference Microplasma Jets'

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Atmospheric pressure microplasmas have gained interest in the past decades in many fields [1] including biomedical applications, primarily due to their efficient production of chemical reactive species e.g. reactive oxygen and nitrogen species (RONS). Many plasma sources have been developed for these applications. One of the challenges in the field is comparability of species components and concentrations across different plasma sources, as this limits comparison and correlation of results in the literature. A plasma source that is relatively simple in design for both simulation and experimental purposes was proposed in the frame of a recent network (COST Action MP1101 'Biomedical Applications of Atmospheric Pressure Plasmas') and presented in [2].

The motivation for the COST Reference Microplasma Jet is as a reference source for atmospheric pressure plasmas and their applications. This reference source should boost fundamental understanding of atmospheric pressure microplasmas, and their interactions with substrates, by making results from different laboratories comparable. For this it is imperative that each plasma jet is reproducible with little variability and has the same characteristics with regards to plasma parameters e.g. power, gas temperature and reactive species concentrations. The COST Reference Microplasma Jet is radio frequency (13.56 MHz) driven across two parallel stainless steel electrodes with a gap of 1mm and plasma length of 30 mm.

In this presentation four COST Reference Microplasma Jets are characterised and compared to each other. Plasma parameters measured include electrical power-delivery, gas temperature of the effluent, optical emission spectroscopy of the core plasma and absolute atomic oxygen densities by means of two-photon absorption laser induced fluorescence (TALIF). In addition, bacterial inactivation, post plasma treatment, is also compared and presented. Escherichia coli MG1655 were selected as a model species. Results indicate very good agreement across the four plasma jets. The challenges of reproducibility and comparing parameters across jets, along with any limitations of the plasmas with regards to biological applications will be presented.


Figure 1. Average absolute atomic oxygen densities, of all four jets, as a function of plasma power for 1 slm helium and 5 sccm oxygen flow 1 mm in front of the electrodes. The shaded area represents the standard deviation of atomic oxygen from all jets and varies between 8 to 13 %. The horizontal error bars represent the error in measured plasma power.
Two-dimensional Vlasov simulations of parametric wave decay and stochastic electron heating

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1University of Strathclyde, UK, 2The Johns Hopkins University, USA, 3NASA Goddard Space Flight Center, USA

High frequency L-O mode electromagnetic waves launched into the ionospheric F-region using RF heating facilities such as HAARP [1] have shown the induced formation of magnetic field-aligned density striations within the ambient ionospheric plasma [1, 2]. These striations are observed in association with lower and upper-hybrid turbulence and significant electron heating within the striation. Initial electron heating to temperatures of >4000K is believed to be a prerequisite for the formation of suprathermal electron tails in the ionospheric F-region by strong Langmuir turbulence [3]. Such tails can result in the ionisation of neutrals and the formation of descending artificial ionospheric layers (DAILS) [4]. In the current context, we present the results of 2D numerical simulations conducted using a Vlasov-Maxwell code [5] to study the mode-conversion / coupling of an L-O mode pump wave to trapped upper hybrid wave eigenmodes of a density striation. Subsequent multi-wave parametric decay is observed leading to lower-hybrid turbulence and high amplitude electron Bernstein waves which (once exceeding the threshold amplitude for stochasticity) can result in significant electron heating. The electron temperatures observed of >8000K in simulation are sufficient to initialise the formation of suprathermal electron tails as a precursor to generating descending artificial ionospheric layers (DAILS).

Plasmas, often referred to as the fourth state of matter, are ionised gases which exist in many forms both in nature, for example the sun, and man-made e.g. plasma displays. Plasma technologies already underpin many existing and everyday applications, from computer and mobile phone chip manufacturing, to space propulsion, sterilisation and human implants. Recently, the potential of plasmas to be exploited for medical applications has been explored.

The ability of plasmas to destroy human tissues and cells has been known for many years - for example lightning strikes. Recent advances have allowed the generation of Low Temperature Plasmas (LTPs) (non-thermal or ‘cold’ plasmas), which can now be harnessed to kill cells in a very controlled manner. LTPs are generated by the application of an electric field across a stream of gas to produce a cocktail of reactive species including biologically active reactive oxygen and nitrogen species (RONS) such as NO\textsuperscript{⋅}, -OH, O\textsubscript{3}, which in combination with the plasma electric field, can interact with cells and their membranes, as well as DNA. This opens up many potential future opportunities for these plasmas, and our presentation will focus on the application to prostate cancer. Plasmas can offer therapeutic alternatives, to for example radiotherapy, for many common cancers. They are relatively cheap to generate, and offer a number of safety advantages, with significantly reduced side effects, over high dose external beam radiotherapy for example.

Our research has applied such plasma treatments to advanced laboratory models of human prostate cancers. We have discovered, by using cells taken freshly from prostate cancer patients, we can not just kill cells using plasmas, but the way the cells die is really important. There are in fact more than four different death mechanisms. Both normal and cancer cells (tested for the first time from the same patient) are susceptible; hence the plasma should be directly applied into the cancers in order to reduce collateral damage to surrounding tissue. LTPs can be created on the dimensions of single cells and propagated down long tubes for local application to the tumour, which we envisage for practical application.

Even at high plasma doses however, there were still cancer cells which survived the treatment. This effect has also been observed using standard clinical treatments, leading to a recurrence of cancer after radiotherapy in one in three patients. We have gone on to measure how the resistance develops, where we observe a primitive stem cell regeneration response, which is activated by the general tissue damage caused by the plasma. This is just like skin damage after a cut, to repair the wound. To use plasmas most effectively as a treatment option for cancer, we have identified a combination of (1) plasma targeting (2) dose optimisation for each patient, and (3) combination treatment with plasma and existing drugs to block the regeneration response will be required.

These studies now should be taken from the laboratory into the clinic for the longer-term benefit of not just prostate, but other cancer patients.

This work was supported by grants from the Engineering and Physical Sciences Research Council (ESPRC), York Against Cancer and generous donations from Beryl and Ron Gatenby.
Wednesday 11 April

(Invited) Guiding laser-produced fast electrons using large magnetic fields

K Lancaster1, D Farley1, J Pasley1, W Trickey1, C D Murphy1, C Underwood1, C Ridgers1, A Home1, P Koester2, R Gray3, Z Davidson3, J S Green4, A P L Robinson4, N Booth4, R Heathcote4, M Notley4, R Clarke4, I Musgrave4 and C Spindloe4.

1University of York, UK, 2Instituto Nazionale di Ottica, Italy, 3University of Strathclyde, UK, 4Rutherford Appleton Laboratory, UK

Currently we are able produce with laser plasma interactions some of the most extreme conditions on earth. When ultra-intense lasers are focused on to solid material, the fields associated with the laser are so strong that electrons can easily escape the atoms in the material. Absorption of the laser pulse results in the generation of a population of relativistic electrons, with currents on the order of Mega Amps. The physics associated with how the electrons are produced and subsequently transported in plasma is complex and proves challenging to diagnose and study. Importantly, these fast electrons are the driver for much of the subsequent physics during these interactions including generation of energetic particles/ photon sources, unique atomic physics states such as hollow atoms, hydrodynamic phenomena, production of warm / hot dense matter relevant to stellar interiors, heating of matter relevant to alternative laser driven fusion schemes such as fast ignition, and conditions relevant for understanding of nuclear astrophysics in the most extreme objects in our universe.

This talk will illustrate some of the experiments happening on petawatt-class lasers concerning how to control important fast electron beam parameters (such as divergence) using novel structured targets. Alex Robinson et al[1] first proposed using targets incorporating a resistivity gradient to confine fast electrons. At the material interface of a high resistivity feature, e.g. a wire, surrounded by a lower resistivity material a strong magnetic field is generated which confines electrons to areas of higher resistivity and higher current density. In this talk experiments using targets with novel silicon embedded features created by Scitech Precision Ltd* using MEMS technology will be presented. A novel duel channel front surface imaging system was created in order to enable both pre-shot alignment and on-shot focal spot position, information critical for performing these types of complex experiments.

* http://scitechprecision.com/

Monitoring of atomic layer deposition processes using remote plasma optical emission spectroscopy

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Gencoa Ltd, UK

Atomic layer deposition (ALD) is a key process in the deposition of many functional thin films. Effective monitoring of these processes is important for reduced setup time of the process as well as detection of contaminants during the deposition.

Conventional residual gas analysers, such as quadrupole RGAs, have difficulty monitoring ALD processes due to the high process pressures (typically above 1E-4 mbar) and the presence of hydrocarbons contained within many ALD precursors. These hydrocarbons often contaminate the RGA filaments, rendering the sensor unusable. For these reasons monitoring of precursor gas concentrations during the ALD process is rarely undertaken.

An alternative gas monitoring sensor that operates directly at pressures above 1E-4 mbar has been built around plasma emission monitoring. A small “remote” plasma can be generated inside a vacuum sensor using an inverted magnetron configuration. Consequently, species that are present within the vacuum become excited in the sensor's plasma, emitting a spectrum of light, which can then be used to identify and monitor the emitting species. Crucially,
this sensing method has been shown to be robust when exposed to the ALD processing environment and can operate at a time resolution that can adequately capture the process dynamics.

This presentation will describe the principle of this sensing method and present examples of its use in monitoring both thermal and plasma enhanced ALD processes that use precursors such as water vapour, ammonia and aluminium and niobium based hydrocarbons.

Local gyrokinetic simulations of tokamak pedestals investigating how magnetic shear affects kinetic ballooning modes

S Biggs and D Dickinson
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Achievement of economical fusion energy using tokamaks faces many challenges, including trying to understand: turbulence; lossy and damaging large-scale instabilities such as edge localised modes (ELMs); and the H-mode pedestal (the region of steep gradients at the plasma edge). One phenomenon involved in all of these processes is that of microinstabilities – instabilities with a length scale similar to the ion Larmor radius. These are the target of our investigations.

Given the length scale of microinstabilities, their study requires a model that retains finite Larmor radius effects. Fully kinetic models of tokamaks are prohibitively expensive in terms of computational cost. Therefore, we employ gyrokinetics, in which we average over particles' helical orbits around magnetic field lines, thus making such calculations computationally tractable. Further computational cost savings can be made by using a local gyrokinetics code, i.e. by solving the gyrokinetic equation along a small bundle of field lines rather than solving within a much larger domain as done in global codes. This approach is particularly desirable since techniques exist to reconstruct the global solution from an array of local solutions. This results in significant computational cost savings compared to performing the global simulation directly while still capturing potentially important global effects.

This talk reports a local linear gyrokinetic study of one particular microinstability, the kinetic ballooning mode (KBM). It is shown that the ordering assumptions used to derive the local gyrokinetic model can be violated in regions of large magnetic shear, such as often found in the pedestal. We then investigate further the role of magnetic shear in the physical mechanism of the KBM instability and discuss implications on local gyrokinetic pedestal simulations.

(Invited) New frontier science experiments campaign on DIII-D Tokamak launched in 2017

M Koepke1, R Butteny2, T Carter3, J Egedal4, C Forest4, W Fox5, H Ji5, G Howes6, P Piovesan7, J Sarff4, F Skiff6 and D Spong8

1West Virginia University, USA, 2General Atomics, USA, 3UCLA, USA, 4University of Wisconsin, USA, 5PPPL, USA, 6University of Iowa, 7CNR-Italy, Italy, 8Oak Ridge National Lab, USA

For the first time, the DIII-D tokamak supplied a multi-day-shot platform for non-fusion-energy-motivated research. The FSE campaign intends to produce impactful publications designed for numerous citations. The purpose is to enable advances in foundational physics understanding and to deepen knowledge on research lines outside of the fusion energy line. The motivation is that DIII-D provides a unique capability to the discovery-science community. The long-range goal is to cross-fertilize with fusion research, with benefits involving fundamental understanding, idea exchange, and collaboration development. List of selected topics for FY2017: (1) Self-organization of Unstable Flux Ropes, (2) Impact of Magnetic Perturbations on Turbulence, (3) Interaction of Alfvén/whistler fluctuations and Runaway Electrons, and (4) Field-line chaos: Self-consistent chaos in magnetic field dynamics. This talk aims to promote the DIII-D FSE concept, help recruitment of future participants, and provide a progress report of FY2017
and FY2018 activities. Based on the outcome, key features of FSE approach were deemed successful by the experimental teams, the DIII-D management, and U.S. DOE. Funding from U.S. DOE is gratefully acknowledged.

Wake potential in relativistic quantum plasma

A A Khan\textsuperscript{1,2} and M Jamil\textsuperscript{1}

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An attractive potential (wake potential) for electron ion plasma was first introduced by Nambu and Akama [1]. Namb et al [2] subsequently extended this idea to dusty plasmas, in order to explain dust crystal formation in laboratory complex plasmas. Khan et al [3] later generalized the wake potential concept in a magnetized semiconductor quantum plasma. Ultradense plasmas have recently attracted attention, due to their appearance in various plasma environments, such as the interior of compact astrophysical objects (white dwarfs, neutron stars) and also in quantum electron plasmas occurring in solid state configurations. In the present work, a quantum hydrodynamic model is employed for the derivation of a dispersion relation for lower hybrid waves in relativistic dense plasmas. The obtained potential has an oscillatory form at very small scale length. In relativistic plasma, we can discuss the crystal structures only in the subsonic region with different external magnetic field and number densities using the wake field approach [4].


HALO - A full orbit code for calculation of the growth and saturation of Alfven eigenmodes

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LOCUST [1] is a recently developed code which leverages the high floating point capacity of modern graphics processing units to perform Monte Carlo simulations of the thermalisation of large numbers of beam injected fast ions in tokamaks. It employs realistic equilibrium geometries, full orbit tracking, sophisticated wall models and a host of well tested numerical schemes to provide high fidelity predictions of the fast ion distribution function and wall power loads in fusion devices.

HAGIS [2] is an established code which uses guiding centre tracking in a flux coordinate system to calculate the power transfer between a fast particle population and an arbitrarily large set of Alfven eigenmodes, thus determining the growth and saturation of the modes.

The HALO (HAGIS-LOCUST) project aims to modify LOCUST to consistently model the evolution of both a fast particle population in full orbit and a set of Alfven eigenmodes, thus combining the functionality of the two existing codes. The new code will allow faster execution times, higher fidelity predictions of growth rates, assessment of the impact of collisions with the background plasma and predictions of heat loads to wall components.

A prototype of HALO is nearing completion. LOCUST has been modified to read in arbitrary numbers of Alfven eigenmodes calculated using the MISHKA MHD stability code and to track the
motion of a fast particle population in response to these modes. Island structures have been observed where resonant particles become trapped within the mode structure, and predictions of the sizes of these structures agree well with HAGIS.

LOCUST has also been modified to calculate the power transfer between the fast particle population and the modes and to update the mode amplitudes accordingly. Work is ongoing to benchmark HALO against predictions from HAGIS for a simple TAE with poloidal mode numbers m=3 and m=4.

Going forwards, a number of research avenues are available. The non-linear evolution of multiple eigenmodes can be explored, collisional physics can be included and the ability to simulate multiple fast species can be considered.


(Invited) Generation and transport of reactive species in a Surface Barrier Discharge
M Hasan¹, A Dickenson¹, A Nikiforov², C Ley², N Britun³ and J L Walsh¹
¹University of Liverpool, UK, ²Ghent University, Belgium, ³Université de Mons, Belgium

Surface Barrier Discharges (SBDs) are one of the most widespread atmospheric pressure discharge configurations. Characterized by a large discharge area, making them ideal for applications requiring uniform plasma on an industrial scale. In such applications, the discharge serves as a low cost and simple source of reactive chemical species under ambient conditions. Recent applications exploiting the unique chemical and physical properties of the discharge include water treatment, CO₂ splitting and microbial decontamination [1]. Critically, in the SBD configuration, reactive species are not only generated, but transported beyond the discharge electrodes through an induced flow of the background gas created by Electrohydrodynamic (EHD) forces [2]. A challenging aspect of the applicability of SBDs to a particular application is determining the spatial distribution of reactive species around the discharge electrodes, as the discharge chemistry is influenced by the flow induced by EHD forces [3]. In this work, a 2-dimensional experimentally validated model is used to analyze the distribution of reactive chemical species in space and time. The physics described in the model has been verified through comparison with Particle Imaging Velocimetry (PIV) measurements to assess the induced gas flow, while the chemistry described in the model has been verified by comparing the calculated species densities to experimental measurements using Laser Induced Fluorescence (LIF) and Fourier Transform Infrared spectroscopy (FTIR). It is demonstrated that the numerical and experimental results show close agreement over a wide set of conditions and that the distribution of NO produced by the discharge is confined to the induced flow region above the surface barrier discharge, while this is not case for other species.

**Magnetic interaction of adjacent laser wakefields in an inhomogeneous plasma**

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Strong magnetic interaction (annihilation, reconnection) in two adjacent laser wakefields excited in a density down-ramp plasma is investigated. Prominent new features concern the generation of well-defined electron vortices drifting transverse to the density gradient and the resulting magnetic field interaction and acceleration of MeV electron beams in the opposite direction of the driving lasers. The formation conditions of the electron vortices and the backward acceleration dynamics are analyzed. These novel features survive the real three-dimensional geometry under elliptical laser spot conditions, better approximating the slab-geometry nature of the problem.


**Spatio-temporal plasma heating mechanisms in a radio-frequency electrothermal microthruster**

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Electrothermal plasma propulsion sources are of significant interest as they potentially allow for power deposition at varying radii within the propellant gas flow. For low power, micro-propulsion sources, further understanding of the mechanisms by which electrical power is coupled to the propellant is useful for increasing thrust efficiency and increasing thruster lifetime through reduced direct heating of material surfaces. Previous studies of radio-frequency (rf) plasmas have shown that the spatio-temporal heating mechanisms are coupled with the local collisionality. This is of importance to thrusters due to the large axial pressure gradient. In this work, phase-resolved optical emission spectroscopy and numerical simulations are employed to study plasma heating in an rf (13.56 MHz) electrothermal microthruster operating in argon at 200 Pa (1.5 Torr) plenum pressure, between 130 - 445 V (0.2 - 5 W). Three distinct peaks in Ar(2p1) excitation are observed, corresponding to three separate electron heating mechanisms within the rf period, namely: field reversal, sheath expansion heating and heating via secondary electron collisions. These findings show close agreement with the results of 2D fluid/Monte-Carlo simulations performed using the Hybrid Plasma Equipment Model (HPEM). The electron heating dynamics are investigated with respect to the rf phase and axial distance with reference to their distinct power deposition pathways. The influence of each mechanism during an alpha-gamma mode transition, where plasma heating is driven via bulk and sheath heating, respectively, is investigated. An increased understanding of how plasma heating processes couple to local collisionality, and hence local gas heating efficiency, is of significant interest to the continued development of more power efficient microthrusters.

**Lethal and sub-lethal effects of laser accelerated protons for radiotherapy applications**

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Among radiotherapy modalities, particle therapy is well known for the highest precision of dose delivery to the tumour. The “dream beam” in radiotherapy should induce maximum lethality in the tumor and completely spare the normal tissue, which is still unachieved as surrounding tissue is always at risk of exposure. An ultra-short delivery time of the localized lethal dose can help to achieve the realization of such a dream beam. The precise delivery of dose at ultra-high dose rate (10⁵-10¹⁰ Gy/s) in short pulses may overload the unstable tumor cell repair processes, while repair-proficient, genomically stable normal cells can still repair any damage inflicted by the particles.
Technological advances using laser-accelerated ions, emitted in ultra-short bursts, offers a future, cost-effective alternative to conventional particle accelerators. Currently, Queen’s University Belfast is leading a consortium of UK universities through the A-SAIL project to advance laser-driven ion acceleration towards medical applications. Here we report on the lethal and sub-lethal effects of these laser accelerated ion beams in human cells for pre-clinical radiobiological characterization.

**Experimental demonstration of a sub-terahertz extended interaction oscillator driven by a pseudospark sourced sheet electron beam**

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The pseudospark (PS) discharge is a form of low-pressure gas discharge, capable of generating extremely high currents within short rise times by means of a hollow cathode structure [1,2]. A high-quality electron beam is generated during the discharge process, which possesses high current density and brightness, as well as the ability to self-focus via ion channel focusing [3]. Simulations have shown that the pseudospark plasma sourced electron beam would propagate within background plasma of density in the range of $10^{14}$ to $10^{16}$ m$^{-3}$ without any applied guiding magnetic field [4]. This makes it an excellent electron beam source for millimetre-wave generation [5].

A pseudospark-sourced sheet electron beam (PS-SEB) has been used to drive a planar slow wave extended interaction oscillator (EIO) structure [6]. Experimental results of the generation of W-band (105GHz) radiation from an EIO based on the PS-SEB will be presented.


**Prediction and analysis of the transition to the avalanching and quasilinear regimes of kinetic resonant modes in tokamak plasmas**

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Many state transitions are observed in tokamak plasmas (such as the L-H mode transition), where a set of parameters allows one to define a threshold between two regimes with differing plasma performance and particle confinement. However, while certain phenomena correlated with fast particle loss in tokamaks are well documented
(Alfvén mode avalanching, phase locking), some mechanisms which enable transitions to fast particle low confinement states are not fully understood.

Here, we use the code DARK to investigate the emergence of Landau instabilities in a 1D collisional plasma with energetic damping, and the subsequent evolution of a set of Landau resonant modes. By examining the behaviour of phase-space holes and clumps on the particle distribution function as BGK modes, we present semi-analytic theories for two dynamical transitions: the transition to the cascading/avalanching regime, and the transition to the quasilinear regime.

Non-stationary plasma modes are said to ‘chirp’ in kinetic systems - crucially, a linearly stable mode can become destabilised as a linearly unstable mode in close proximity in k-space (in turn, close proximity of resonance in v-space) undergoes chirping. We find that modes that are close to marginal stability prior to destabilisation are more likely to chirp, leading to the further destabilisation of neighbouring modes in phase-space. We propose that a single measurement of the lifetime of a single mode chirping event can allow for the prediction of the required mode spacing for avalanching.

A set of stationary-frequency modes is shown to transition to the quasilinear regime when the modes undergo suitable mode overlap. Bouncing particles that were previously segregated are shown to begin to inhabit the same resonance broadened region of phase-space, allowing us to give an analytic criterion for the quasilinear transition.
Synthetic divertor diagnostics for integrated data analysis at MAST-U with ray-tracing

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The charge-exchange recombination and beam analysis (CHERAB) code was developed at JET as a powerful framework for modelling spectroscopic diagnostics with ray-tracing. The framework is capable of handling detailed 3D engineering geometry and realistic first-wall material reflections. In this work, CHERAB will be applied to the full suite of MAST-U spectroscopic divertor diagnostics with the aim of enabling integrated data analysis during MAST-U operations.

The three principle diagnostics being examined are the bolometry, filtered cameras and divertor grating spectroscopy systems. For each diagnostic, the benefits of the ray-tracing approach are demonstrated and compared against the more conventional line of sight approximation. Bolometry is a diagnostic particularly sensitive to geometry effects due to the effect of volume sampling, and is typically ignored in the data analysis techniques currently in use. In the CHERAB model, the bolometer foils are ray-traced as ray bundles with a “path tracing” algorithm. By using the full 3D machine model, geometry effects such as occlusion and vignetting are included in the étendue calculations, having a demonstrable effect on the radiated power inversions.

The filtered camera model allows inclusion of realistic first wall reflections from metallic components and carbon tiles. Using the full first wall model for MAST-U, reflections can be studied to understand their likely impact on the measurements and associated artefacts in tomographically reconstructed data. Additionally, using volume ray-tracing instead of single sight-lines leads to less aliasing in the camera’s inversion weight matrix.

The CHERAB code has been designed to integrate with the ADAS framework for modelling impurity line radiation in the divertor, including effects such as electron impact excitation, recombination, charge exchange and stark splitting. The resulting models allow detailed predictions of our measurement capabilities in MAST-U, and the investigation of line integration effects on plasma parameters estimated via spectroscopy in unprecedented detail in a tokamak environment.

Although its primary application domain is fusion plasmas, CHERAB was designed as a general framework and could find application in many areas of plasma physics such as astrophysical and industrial plasmas. Some example applications will be explored.

Out-of-band extreme ultraviolet emission from a droplet-based laser-produced Sn plasma source

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We present the results of spectroscopic measurements in the extreme ultraviolet regime (EUV, 7 – 18 nm) of the light emitted by liquid Sn microdroplets irradiated by a high-intensity Nd:YAG laser at its fundamental wavelength (1064 nm) [1]. Droplet-based, laser-produced EUV plasma sources are of particular technological interest due to their relevance in the nanolithographic industry [2]. We investigate the out-of-band (i.e. with wavelength different
than 13.5 nm), atomic line emission between 7 nm and 12 nm generated by the high-density laser-produced Sn plasma. Using atomic structure calculations carried out with the Flexible Atomic Code [3] and local thermodynamic equilibrium arguments, we show that the measured spectroscopic features can be explained by electric dipole transitions from high-energy configurations towards the ground configurations within the Sn\textsuperscript{8+} - Sn\textsuperscript{15+} ions. These are the very same ions responsible for the valuable 13.5 nm photons in nanolithographic EUV sources [4,5]. Our results provide valuable diagnostic information as they could be employed to identify the charge state contribution to the measured spectrum.


Optical imaging spectroscopy of magnetised plasmas

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Diagnostics of magnetised plasmas is challenging because of the gyration of plasma species. Well established methods such as Langmuir and optical probes can produce erroneous results. For example, the Langmuir probe current-voltage characteristic becomes distorted in the electron retardation region in weak magnetic fields [1]. The problem is further compounded by the increased complexity of the underlying probe theories [1]. Relatively large optical probes [2] can also perturb the plasma leading to uncertainty in the plasma parameters. Furthermore, in both methods multiple measurements have to be acquired in different positions in order to build up a spatial map of plasma parameters. This is both time consuming and data analysis is labour intensive.

Plasma imaging techniques readily obtain both spatial and temporal maps of the plasma emission removing the need for multiple scans with reduced data processing. However, parameters such as the local plasma density and temperature are not obtained. For example, phase-resolved optical emission spectroscopy (PROES) [3] obtains the temporal evolution of the excitation function in RF plasmas. This provides qualitative information on the energy coupling mechanisms such as sheath expansion, sheath reversal and the role of secondary electrons.

In [4] a line ratio imaging technique was used to obtain qualitatively an electron temperature and density map in a dusty plasma. Here, we show how this technique can be quantified and extended to obtain both the average electron density and temperature maps of the entire plasma. Results will be presented in both a unmagnetised and magnetised parallel plate capacitively coupled radio-frequency plasma. The figures below show time averaged and line integrated density and temperature maps at 60 mT. Non-uniformity of the plasma is clearly seen with an enhanced density region and cooler electrons in the field direction and a non-uniform sheath adjacent to the driven electrode.
Deposition removal from fusion optics

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Within a fusion reactor the optical component of any diagnostic closest to the plasma is called the first mirror. The energetic atoms formed by charge exchange within the plasma can bombard the mirrors and erode the surface. This same erosion process occurs on the nearby first wall and causes the deposition of this material on the mirrors. These processes cause degradation of the reflectance of the mirror surface and therefore degradation in the quality of the signal reaching the diagnostic. Erosion is easily overcome using either single crystal or small scale crystal structures, however degradation caused by deposition is substantial and still requires a sufficient solution.

Low-temperature plasma removal of these fusion depositions is a potential way of maintaining the reflectivity of the mirrors in-situ. This involves creating a capacitively coupled plasma using the mirror as the electrode. Experimentally this has been tested and provides good results [1,2], however these have used aluminium oxide as a proxy for the beryllium set for use as the first wall in future fusion devices. It is also not possible to test all individual mirror placements or magnetic field geometries. Using the Hybrid Plasma Equipment Model (HPEM) it is possible to simulate the conditions and chemistry as close to the working environments as possible [3]. This allows us to understand the plasma and work towards optimisation of the removal process by varying operating parameters, such as frequency, voltage, pressure, and power. By also investigating gas mixtures we can combine the ion bombardment with chemical etching.

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Envelope solitons in collisional superthermal plasmas: the role of dissipation and suprathermal particles

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Focusing on the modulation dynamics of high frequency electron acoustic waves [1] in multispecies, unmagnetized, collisional superthermal plasmas, a cubic nonlinear Schrödinger equation (NLSE) with real dispersive term and complex nonlinear term is derived, by adopting a multiple scale perturbative approach [2]. Energetic electrons are considered, modelled by a K-type long-tailed distribution [3, 4]. Electron-neutral collisions [5] are taken into account via an ad hoc damping term. The existence and dynamics of dissipative electron acoustic envelope modes (solitary waves, SWs) is investigated, via linear and nonlinear analysis. The parametrical dependence of the propagation characteristics of dissipative envelope modes (amplitude, width, speed) on the plasma configuration and on the superthermality index k is investigated.

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TOF-based diagnostics system for high-energy laser-accelerated proton beams

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Thanks to advances in laser technologies, all-optical acceleration of high-energy ions at high repetition rate is becoming a reality and is opening new opportunities for using laser-accelerated ion beams for medical applications, including hadrontherapy. Beam diagnostics able to characterize energy spectrum and particle flux, are crucial to delivery controlled beams as required for applications. For this purpose, Time Of Flight (TOF) techniques coupled with detectors such as Faraday cups and ion collectors, so far extensively used with low-energy laser-driven ion beams as reported in the literature [1], are particularly suitable for the on-line measurement of such important beam parameters.

Nevertheless, diagnosing high-energy ion beams requires the use of fast detectors, providing the high temporal resolution required to disentangle the high-energy component of the beam [2,3,4].

An on-line diagnostics system based on the Time Of Flight (TOF) technique coupled with diamond and/or silicon carbide detectors has been developed to fulfill this requirement and will be presented in this contribution. Several characteristics make these kinds of detectors particularly attractive for timing measurements with high-pulsed and high-energy ion beams, namely the radiation hardness, the fast time response and the high signal-to-noise ratio.

A new analysis procedure to extract the energy distribution for a given ion species from the TOF signal, optimized for high-energy laser-driven proton beams, has been developed and will be discussed.

Recently, the diagnostics system has been tested during an experimental campaign carried out at Rutherford Appleton Laboratory (RAL, UK) with high-energy laser-driven proton beams accelerated by the PW VULCAN laser. In particular, the analysis procedure was validated by comparing the results obtained with TOF detectors, with well-
established single-shot diagnostics such as Thomson Parabola, nuclear track detectors (CR-39s) and Radiochromic films (RCF).

The results that will be presented, confirmed the reliability of the TOF technique and of the analysis and highlight the suitability of this detection method for on-line diagnosis of high-energy ion beam characteristics.


Characterisation of the plasma filled rod pinch diode operation
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The plasma filled rod pinch diode (aka PFRP) offers a small radiographic spot size and a high brightness source. It operates in a very similar way to plasma opening switches and dense plasma focus devices - with a plasma prefill supplied by a number of simple coaxial plasma guns, being snowploughed along a thin rod anode before detaching at the end.

The aim of this study is to model the PFRP and understand factors that affect its performance.

Given the dependence on the PFRP on the prefill, we are making detailed measurements of the density (10^{15} - 10^{18} /cm^{3}), velocity, ionisation and temperature of the plasma emitted from the guns. This information will then be used to provide initial conditions to the Gorgon 3d MHD code, and the dynamics of the PFRP operation will then be studied.

(Invited) Tailoring intense laser fields for the generation of bright XUV pulses from plasmas

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Intense laser interactions with plasma surfaces are an exciting and unique approach to generating beams of coherent extreme-ultraviolet (XUV) or even X-ray radiation with attosecond scale temporal structure. The mechanisms are tied to the motion of electrons at the plasma interface which can form short, dense bunches that emit high frequency radiation coherently. Here, we explore the possibilities of controlling this process by precise tailoring of the intense electromagnetic fields in the driving laser that is responsible for steering these electron bunches. We show experimental results [1] demonstrating that fine tuning of the sub-cycle timing of an added co-propagating second harmonic laser pulse allows significant modification of the incident waveform which in turn can lead to large increases in the energy of the emitted XUV radiation. Using simulations, other routes to controlling the
exact laser field structure are studied and the influence of some characteristics of the plasma target are considered. These techniques have the potential to bring intense coherent XUV sources into a laser laboratory setting with the unique advantage of near-perfect synchronicity with the driving laser pulse which is essential for accurate time-resolved pump-probe experiments.

(P1) Withdrawn

(P2) XUV absorption in warm dense aluminium

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The collisional absorption of soft x-rays in warm dense aluminium remains an unresolved question; experiments have been conducted previously to determine this but produced inconclusive results. The experiments involved generating x-rays from palladium foils to heat an aluminium foil target to a temperature of ~ 1eV. A laser driven high-harmonic beam from an argon gas jet was used to produce a probe beam at 21eV, 26eV and 31eV photon energies. Here preliminary experimental results are presented from a revised version of the previous work; these data are expected to allow much more precise measurement of the absorption. Potential future work is also described as changing the probe drive gas would allow data to be gathered over a much wider range of photon energies.

(P3) Impact of plasma physics and engineering constraints on a fusion neutron source for a transmutation system

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Effects of plasma physics and engineering constraints on the optimal configuration of a fusion-driven system that uses a Tokamak-type fusion reactor as a fusion neutron source to drive the sub-critical fission reactor blanket are investigated. For self-consistent determination of the configuration of the system components, a tokamak systems analysis coupled with a radiation transport calculation is used. The inboard radial build of the reactor components is obtained from plasma physics, engineering constraints and radiation shielding requirement, while outboard radial builds are mainly determined by the requirements on neutron multiplication, the tritium-breeding ratio, and the power density. The effects of a tritium-breeding blanket model and an equilibrium fuel cycle on the radial build as well as the transmutation characteristics are also investigated. It is shown that the radial build of the transmutation reactor components and the equilibrium fuel cycle play major roles in determining the transmutation characteristics.

(P4) Withdrawn

(P5) Phase mixing of large amplitude relativistic electron plasma oscillation with inhomogeneous ion background

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Phase mixing of relativistic large amplitude nonlinear plasma wave in presence of a time independent space periodic ion density profile has been investigated.[1,2,3] Inhomogeneous ion along with the relativistic variation of electron mass make the characteristic frequency of the wave to acquire a space dependency and thereby it breaks
at arbitrarily small amplitude due to phase mixing.[4,5] An approximate space time dependent solution is obtained in the weakly relativistic limit by Bogoliuboff and Kryloff method of averaging. We find that the change in the ion density perturbation and also the relativistic electron mass variation have significant effect in modifying the time at which phase mixing occurs.


(P6) CCP-Plasma and Plasma-HEC: UK funded networks for computational plasma physics and high-end-computing
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The Collaborative Computational Project in Plasma Physics (CCP-Plasma) was established in 2007 with the aim of pooling the collective expertise and developing core plasma physics simulation codes, and training packages, for UK science. A companion project is the Plasma High-End Computing (Plasma-HEC) Consortium. Plasma-HEC supports research in the simulation of plasmas which specifically need access to Tier-1 national computing resources. This poster summarises the organisation of both CCP-Plasma and Plasma-HEC, their current status and recent achievements.

(P7) K-edge shift under warm dense matter conditions
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One way to look at the electronic structure of Warm Dense Matter (WDM) is through the K-edge shift for shocked compressed matter. For a dense plasma of several times solid density, the continuum lowering shift due to the micro-field of the plasma can be on the order of 10s of eV or more. However, the net K-edge shift is lower than this since there are three different factors which can affect the K-edge shift. The first one is the continuum lowering as already mentioned which causes the K-edge energy to be lowered and causes a red shift. The second is due to ionisation of the matter being probed. This causes the electrons to be more tightly bound to the ions and results in a blue shift in the energy of the K-edge. The final effect is that due to degeneracy and can result in the K-edge being blue or red shifted along with being broadened, as the electron velocity distribution function follows a Fermi-Dirac distribution.

There are different models that can describe continuum lowering in a hot dense plasma. Two of these are the Stewart-Pyatt model and the Ecker-Kroll model. For systems which are highly ionized the Ecker-Kroll model predicts that the threshold energy required to ionize an ion to the continuum is much lower than that of the Stewart-Pyatt model. Recent experimental data from X-ray laser facilities and large laser facilities disagree on which model best describes continuum lowering (see [1] and references within) and as such has rejuvenated interest in this area of research.
In this study we are motivated by this recent disagreement in results of continuum lowering and hope to improve upon the experimental work of Bradley et. al [2] and Riley et. al [3] at the Central Laser Facility (CLF) in 1987 and 1989 respectively. This work showed how the K-edge of chlorine (Cl) varied with increasing temperature of a potassium chloride (KCl) target as it was compressed.

An experimental campaign to explore WDM K-edge shifts was conducted between July-August 2017 at VULCAN Target area west at the Central Laser Facility, UK. Two different sample types, one consisting of KCl and the other of chlorinated parylene-C, were used. A WDM sample was created by irradiating both sides of the targets with the 6 long pulse beams (3 per side) to drive a shock. To probe the targets a broadband Bi M-shell x-ray source covering the spectral region around the K-edge of the Cl was used, produced by two short 200 ps (527 nm) pulses that irradiated Bi back-lighter foils on either side of the shocked sample placed 45 degrees from target normal at a timing separation of 400 ps.


(P8) Ultrafast dynamics of liquid water irradiated by picosecond proton pulses

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Across many areas of radiation chemistry, the characteristics and behaviour of the solvated electron has been extensively studied since its discovery in 1962. When ionising radiation reacts with water molecules, these solvated electrons are produced and have the potential to cause unrepairable damage to DNA, making them a desirable by-product for applications in radiation biology. Although the solvated electron is responsible for an adequate amount of DNA damage, it is out performed by the 60-70% of cellular damage caused by hydroxyl radicals, another resultant species of radiolysis.

Recently experiments have been performed using the TARANIS laser facility at Queen’s University Belfast (800 fs, 1053 nm, 20 J). We have examined the dynamics of solvated electrons through the interaction of laser-driven protons with water in the form of an ion-induced opacity. By using a pump-probe technique with a high degree of synchronicity, the evolution of the opacity is observed on a sub nanosecond scale (10^-9 s), probing the reaction during and immediately after the proton interaction with the water. This evolution is monitored by examining the onset and recovery of the opacity upon reaction, and any underlying processes which could potentially be affecting the waters oxidation and recovery are discussed along with a strategy for adapting the experiment to observe the evolution of the hydroxyl radical and other products of radiolysis.

This poster will describe work carried out at QUB to characterise atmospheric pressure plasmas, like the one shown in figure 1. These plasmas are currently of great interest due to their wide range of applications, particularly in plasma medicine, such as sterilisation and wound healing [1]. The aim is to investigate plasma parameters such as electron temperature and density, gas temperature and the plasma bullet velocity using diagnostics such as laser scattering, spectroscopy and bullet imaging. Bullet imaging has revealed that although it looks like a continuous plasma jet to the naked eye, it is in fact a series of plasma bullets travelling at velocities of up to 75kms⁻¹.

Raman scattering in air with and without helium flowing through the system is shown in figure 3. These results can be used to find the rotational temperature T_rot.

Future work will include the setup of a triple grating spectrometer which will allow us to distinguish between the three scattering mechanisms present; Thomson, Rayleigh and Raman scattering.

(P10) Study of Ar Photo-ionisation Physics using VULCAN

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This poster will describe a photo-ionisation experiment carried out at the CLF. The aim was to photo-ionise Argon gas using L-shell x-ray line radiation, produced by a laser irradiated tin (Sn) foil target, therefore producing a photo-ionised plasma. We wished to achieve a higher value of $\xi$ (photo-ionisation parameter) than has been obtained previously in this type of experiment [1, 2], where values of $\xi = 6-25$ erg cm$^{-1}$ have been achieved.

A gas cell was used which allowed the density of the gas to be controlled and once the chamber was placed under vacuum, the cell was filled with argon at pressures between 50-1500 mBar.

![Figure 1. Images obtained using Mica spectrometer](image1.png)

Figure 1. Images obtained using Mica spectrometer

a) With Al target  
b) With Sn target

Figure 1 shows spatially and spectrally resolved results with a spherical mica crystal spectrometer with (a) Al and (b) Sn foil targets. The $k_{\alpha}$ and $k_{\beta}$ emission from the argon in 1b illustrates that we have achieved photo-ionisation of argon gas, while the results with the Al foil target confirm that the emission is driven by radiation rather than plasma. Higher values of $\xi$ were also achieved, as high as 45 erg cm$^{-1}$, which are, to our knowledge, the highest to be achieved in the laboratory.

An extension of this study has recently been completed at the Shenguang II Laser Facility in Beijing, China, with promising results obtained.


(P11) High flux table-top synchotron radiation from a compact plasma waveguide

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We investigate synchrotron radiation from a short compact plasma waveguide. When a linearly polarized laser pulse propagates in the waveguide, the pre-accelerated electrons by the excited surface waves on the wall of the waveguide can be injected into traverse fields of HE11 modes and are accelerated to very high energies via the DLA regime. The oscillations of these electrons in the traverse fields and the quasi-static electromagnetic fields force the
electrons to emit high-flux X-ray photons with energy up to 300keV. The critical energy and the radiation power are tunable through the laser intensity and the diameter of the waveguide. Compared to the synchrotron radiation from the target with the near critical density, the divergence is controlled in 5°, the corresponding yield of photons reaches to 1.7x10^{11} with a 90TW laser pulse. The corresponding flux is estimated to be 3.5x10^{21} photons/s · 0.1%BW.

Acknowledgments

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(P12) In search of line coincidence photopumping

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Following preliminary measurements in 2013, the first dedicated attempts were made on the Orion Laser to observe line coincidence photopumping – the enhancement in population of an atomic level brought on by absorption of x-rays from a different emitting ion. The two lines are said to be resonant, or close enough in energy, such that line emission from one can be absorbed by the other, promoting an electron to a higher state. This then decays via intermediary states to the ground. It is the characteristic signal of this decay that we look for. Detection relies upon use of the XUVGS (X-ray Ultra-Violet Grating Spectrometer), covering the 120 to 1200 eV energy range coupled to a gated x-ray detector. High temperature and low density are required to give a significant population of H-like chlorine at the correct optical depth to see pumping. To this end, up to eight of Orion’s long pulse beams were used to heat the tamped potassium chloride targets. This was varied over the six shot days to provide a range of conditions.

Data analysis is well underway, underpinned by modelling. There is a clear signal from the characteristic line in chlorine and evidence will now being collated to assess enhancement compared to a scenario where no pumping occurs.

(P13) Pure proton beams accelerated by the interaction of intense laser pulses with thin cryogenic hydrogen ribbons

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Acceleration of protons and ions using ultrashort intense laser pulses is a very active area of research with multidisciplinary applications in industry and medicine. Ions are typically accelerated via the target normal sheath acceleration (TNSA) mechanism [1], whereby the laser generates a hot electron sheath at the rear surface of the target, creating a very large electric field due to the charge separation, which accelerates protons and heavier ions
Present on the target rear surface to MeV energies, over much shorter distances compared to conventional RF accelerators. Typically targets consist of flat foils made from metallic or insulating materials. The ion beams generated can contain multiple different elements and ionisation states. Usually, a pure beam consisting of a single species, such as protons, is desired for applications. While protons can be separated from multispecies beams by the use of appropriate selection systems, there are clear advantages in using a pure hydrogen target, and thus producing pure proton beams directly at the source.

Presented here are the results of an experimental campaign recently undertaken on the Petawatt arm of the Vulcan laser system in the Central Laser Facility in the UK. In the experiment ELISE, a novel cryogenic system developed at CEA delivering thin (75 – 100 μm) ribbons of solid hydrogen, was used as a target. The interaction of a 1ps pulse with an intensity up to $5 \times 10^{20}$ W/cm$^2$ produced beams of protons with a maximum energy exceeding 55 MeV, and with no detectable contaminants. This was then compared to results obtained with plastic and gold targets. This far exceeds previously reported energies for cryogenic hydrogen targets [2], and serves as a proof of principle study for the benefits of using solid hydrogen as a target in future laser experiments.


(P14) Withdrawn

(P15) On the effect of plasma composition and highly energetic electrons on plasma expansion into vacuum

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Plasma expansion into vacuum has recently been attracting significant attention, due to its relevance with experiments on ultraintense laser pulse interaction with solid targets [1]. Using one spatial and one momentum dimension (1D-1P) in a three-species, relativistic Vlasov solver code, Robinson et al showed that changing the composition of a homogeneous target composed of protons and a heavy ion species, the maximum proton energy is changed [2]. As in most earlier works, the electrons were assumed to be isothermal throughout the expansion process, and a (one) single ion species was considered, for simplicity [3]. However, in more realistic situations, the evolution of laser produced plasmas into vacuum is mainly governed by nonthermal (highly energetic) electrons. These electrons are characterized by particle distribution functions with high energy tails, which may significantly deviate from the Maxwellian distribution [4]. Furthermore, laser produced plasmas may contain several ion species [5].

In this paper, we present an analytical model for plasma expansion of a two component plasma with suprathermal (nonthermal) electrons, modelled by a kappa-type distribution [6]. The effect of energetic electrons and of the secondary ion species on the ion density, velocity and the electric field is investigated. Different special cases are considered, as regards the relative magnitude of the ion mass and/or charge state.

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In ionospheric heating experiments radio waves of frequency 2-10MHz are launched upwards into the Earth’s natural ionospheric plasma and excite nonlinear phenomena near the reflection point. In the first few tens of milliseconds after switch-on Langmuir turbulence involving the excitation of secondary Langmuir and ion-acoustic waves/oscillations is believed to be the dominant nonlinear effect [1].

Computational descriptions have usually involved treating the input electromagnetic wave using a reduced model. The secondary electrostatic waves are then treated in a local model with assumed driver wave and locally homogeneous plasma parameters, typically using periodic or quasi-periodic boundary conditions [2,3,4]. However, another approach involves holistic simulations in which the electromagnetic wave of wavelength order several 100m is modelled simultaneously with electrostatic waves of size order 10cm [5], allowing for a more complete description at the cost of greater computational load.

We present recent progress with this multiscale approach involving the extension to a quasi-2D fluid model and a 1D Vlasov simulation including comparison of secondary electromagnetic emission (SEE) spectra.

produced from such interaction are with broad energy spectrum and a wide beam divergence which are undesirable for many applications. A recent concept utilising miniature helical coils that harness the extremely high electromagnetic pulses from the laser-target interaction has been demonstrated capable of simultaneous focusing, energy selection and post-acceleration of the ion beams [2]. Ions synchronously propagating with the electromagnetic pulse are boosted in energy by the longitudinal component of the electric field, whereas the transverse component pushes the ions towards the helix axis reducing beam divergence. Such helices can additionally be employed sequentially to further post-accelerate the transiting ions. Recently a proof of principle experiment was performed using the Titan laser beam, providing 250J in short pulses of 600fs, at the Lawrence Livermore National Laboratory in California. A two stage geometry was employed by splitting the laser into two halves, each interacting with a separate helix target. This arrangement allowed the second helix's effect on the ion beam to be studied by varying the time delay between the two half beams, which will be presented along with particle tracing simulations.


(P18) Investigating the response of gafchromic EBT3 films to high LET radiation

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Gafchromic radiochromic films, in particular the EBT3 type, are a popular radiation dosimeter in healthcare and related research activities. Although the films’ optical density response is indistinguishable when irradiated with either photons or high energy protons (>10MeV), it was found that there was an under-response when using low energy protons (4MeV) in comparison with that of photons[1]. As such, an investigation was carried out in the LNS-INFN facility in Catania to determine if the response of Gafchromic EBT3 films to charged particle irradiation is solely dependent on the LET (Linear Energy Transfer) of the incident particle, or if there are other key parameters in play, such as their atomic mass.

The low energy proton and carbon ion beams, accelerated by the LNS TANDEM, were used to deliver doses between 0.25-5 Gy to customized films of EBT3 (where a protective top layer had been removed from the films). Thereafter, high energy Oxygen and Carbon ion beams (75MeV/nucleon and 45MeV/nucleon respectively) of the same value of LET (70keV/µm) were accelerated and directed from the LNS cyclotron to determine if the LET plays an important role towards the EBT3 response. For instance, if the dose responses were differed significantly, it would have been clear that the LET is not the main parameter.

From the preliminary data obtained in the low-energy part of the experiment, a calibration of EBT3 response to high LET Carbon ion data was achieved for low doses (<3 Gy). However, due to some variations in the reference proton beam, causing large uncertainties at higher doses, further work is required to extend this calibration to higher doses. In the high-energy part of this experiment, the compiled data indicated that differing ion species is not a key factor in affecting the EBT3 response. As such, this data provides a plausible indication that the LET is the main parameter to be taken into account in determining EBT3 film response.
(P19) Commissioning and initial experiments of an EUV capillary discharge laser

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Capillary discharge lasers produce radiation in the extreme ultra-violet (EUV) at 46.9nm. A population inversion is produced by a high voltage electrical discharge passing through an argon filled capillary tube. Radial pinching of the argon plasma within the capillary, through the \( J \times B \) force causes the pressure and temperature of the plasma to increase which causes amplification of \( 3p - 3s \) (\( J=0-1 \)) transitions creating EUV lasering by amplified spontaneous emission. The plasmas formed by the EUV laser irradiation of solid targets can be shown to produce warm dense matter in a regime where the ionization equilibrium is dominated by radiative ionization.

Initial experiments using a capillary laser with pulse energy of 50\( \mu \)J and pulse duration of 1.2ns are described. The laser has been focused using a single on-axis gold mirror and there is potential to use a scandium-silicon multilayer mirror. With estimated reflectivities of 10% and 50% respectively irradiances on solid targets between \( 1 \times 10^{11} \) Wcm\(^{-2} \) and \( 3 \times 10^{12} \) Wcm\(^{-2} \) can be produced. The laser optimisation, calibration and designs for initial experimented are presented.

(P20) Proton array focused by a laser-irradiated mesh

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Small divergent and quasi-mono-energetic proton beams are vital for proton applications [1]. There are several methods for proton beam control [2]. Building on previous work [3,4] on transient fields generation and transport in laser-plasma interaction, we propose a novel approach which, with the help of the transient fields spreading across a mesh target, allows obtaining an array of multiple focused proton beams (see FIG(a)).

This has been experimentally realized by employing a copper mesh irradiated by a laser pulse with energy of \( \sim 3J \), at an intensity of \( 2.1 \times 10^{18} \) W/cm\(^2\). Transient fields are established on the mesh and sustained for more than \( \sim 35 \) picoseconds. A 0.8-\( \mu \)m wavelength laser pulse (CPA1) with a duration of 50 fs and energy of 12.3 J is focused onto a 4-\( \mu \)m Al foil for proton generation by target normal sheath acceleration (TNSA). If the protons reach the mesh during the presence of the fields, they are acted upon by the fields. Under the effect of the collisional and electrical forces from the mesh, a laser-driven proton beam is split into multiple focused beams with high density after propagation through the charged-up mesh (see FIG(b) and (c) ). Multiple beams focusing through this approach may open new routes for proton beam conditioning, opening up novel opportunities for multi-beam applications, such as multi-point probing, three-dimensional radiography and proton fabrication/lithography.

On the basis of the analysis supported by PIC simulations, we know that the electric fields generated on the mesh maintain the periodic structure of mesh. Within each grid element, the electric fields reach their peak, with amplitude \( \sim 10^8 \) V/m, along the copper wire boundary, while the field amplitude is zero at the center of the grid. Such a pattern is suitable for beams focusing as demonstrated in the experiment.
Plasmas produced in saline solutions were observed with a fast framing camera and simulated with a finite element method software. A pin-to-plate electrode configuration immersed in saline solution was used with the ground electrode lying at the bottom of the container; medium voltage (100s V) pulses, ms long, were applied to the tip. Initially, liquid adjacent to the tip is vaporized [1]. The vaporization was recorded with a fast framing camera which allowed the calculation of the electric fields using a finite element analysis [2]. It has been found previously that discharges are contained inside this vapor layer [3]. Fig. 1 shows consecutive frames for 1.8% NaCl solution and a -160 V / 10 ms pulse. The plasma model with water chemistry cross-sectional data and Arrhenius parameters used the geometry shown in Fig. 2. Estimated electron density, for example, is shown in Fig 3 with a peak frame value $n_e=2.1\times10^{11}$ cm$^{-3}$. Note that experiment (Fig. 1) and simulation (Fig. 3) both show plasma density separated from the tip.
Figure 2. Geometry used for plasma chemistry modelling.

Figure 3. Electron density calculation at 1.55 μs after the application of voltage.


(P22) Withdrawn

(P23) Capillary Z-pinch plasma generated by impulse transformer

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The X-ray lasers and waveguides based on capillary discharge Z-pinch plasmas require the pump pulse with fast (a few hundreds nanoseconds) half-period and high (a few tens kiloamperes) amplitude. Such pulses are usually produced by high-voltage (up to ~ 800 kV) Marx-generators in a C-C charge-transfer scheme. The capillary X-ray lasers and waveguides can operate by using Z-pinches with lower amplitude (I_p ~ 5 kA) pulses and shorter (T/2 ~ 100 ns) current half-periods. The current pulses with such parameters have been produced by using an impulse transformer in Ar^+8 (λ = 46.9 nm) capillary lasers [1, 2]. This pumping system employs a hybrid system based on impulse transformer powered by a Marx-generator. The use of hybrid system has reduced requirements of the Marx-generator's technical parameters (charge voltage and size).

The research procedures aim at developing a compact, low charge-voltage pumping system based on an impulse transformer without using Marx-generator, in order to generate pumping pulses with amplitude of ~ 5 kA and ~ 50 ns rise time. The pulses with such parameters could be sufficient to achieve the waveguiding effect and X-ray lasing of the Ar^+8 ions. The MHD simulations have showed that the lasing and waveguiding effect occur at high electron density (N_e ~ 10^{17} - 10^{18} cm^{-3}) of the capillary plasmas [3].
The present study describes the results of the development and experimental investigation of the pumping scheme based on a 1:4 step-up impulse autotransformer. The ~ 70 J energy of the transformer is stored in the capacitors. In case of ~ 25 kV primary-winding voltage, under optimal conditions, we achieved 90 - 100 kV output pulses with current-amplitude of ~ 5 kA and half-period of ~ 80 ns. Properties of the laser and waveguide plasma channels have been analyzed by using our MHD model for different parameters of the pumping scheme.

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(P24) Waveguide properties of the capillary Z-pinch plasma

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The ability of the capillary discharge plasma column to guide high intensity laser pulses is widely used in laser driven plasma wakefield acceleration (LWFA) experiments [1]. In the absence of such guiding channel, the interaction length is basically limited by diffraction to distance of order of the Rayleigh-range [2]. Further limitation of the interaction length can be caused by ionization-induced refractive defocusing of partially ionized plasmas. In order to avoid partial ionization, most of the research groups deal with hydrogen-gas filled micro-capillary discharge waveguides, in which the guiding core is extended to the whole capillary cross section, i.e. the effects of the wall are inevitable. Nevertheless, in some experiments other gases were used. For example, Higashiguchi et al. have reported on Ar-plasma waveguide produced in alumina capillary, where the ionization state of Ar-ions and spectrum of the propagated laser pulse were measured and simulated [3]. Concerning the wall effects, according to one-dimensional MHD model simulations of the capillary Z-pinch plasma, a transient pure plasma waveguide channel can be evolved without any influences of the wall.

Results: The goal of our study is to reveal how useful such guiding channel can be for the LWFA. The waveguide properties of the Z-pinch plasma inside a 3 mm inner diameter and 200 mm long Ar-gas filled capillary channel were theoretically investigated. For the irradiation a TEM00 mode of Nd:YAG or CO2 pulsed laser was used with FWHM of 0.1 and 1 ps, respectively. In terms of experimental feasibility, intensity of both lasers was set to value to reach the high enough contrast between the laser modes and plasma radiation. Wave optics simulations showed, that in accordance with phenomenological formulation of the matched spot size [4], there is a time range during the discharge, when the input parameters of the coupled laser beams (FWHM and the peak intensity) remain nearly constant over the whole capillary length, i.e. single mode transmission takes place. From the aspect of LWFA experiments, it is important that the laser pulses suffer a slight distortion in spectral range at the capillary output.

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[3] T. Higashiguchi, N. Bobrova, P. Sasorov, S. Sakai, Y. Sentoku, R. Kodama, and N. Yugami,
(P25) Effect of current diffusion on the inter-ELM pedestal evolution in JET-ILW type I ELMy H-mode plasmas

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In a high confinement mode (H-mode) tokamak plasma the energy and particle transport at the edge is reduced and a narrow region with steep pressure gradient is formed, called the pedestal. High pedestal pressure leads to higher core pressure, thus optimising pedestal confinement is beneficial for fusion performance. However, the steep edge pressure gradient can trigger Edge Localised Modes (ELMs), periodic instabilities transporting energy and particles out from the plasma leading to high heat loads on the plasma facing components. Understanding the physical processes governing the behaviour of the edge pedestal is crucial in order to predict the plasma performance in future devices such as ITER.

According to the Peeling-Ballooning (P-B) model [1], [2], coupled P-B modes limit the pedestal growth and trigger an ELM. In this model, edge current density can stabilise ballooning modes through reduced magnetic shear or drive peeling modes, and pressure gradient can drive ballooning modes. Recent studies on JET with the Be/W ITER-like wall (JET-ILW) [3], [4] have shown that in high beta discharges with high D2 gas rates the inter-ELM temperature pedestal growth is saturated half way through the ELM cycle, leading to plasmas with reduced confinement. The linear MHD stability of these pedestals is inconsistent with the Peeling-Ballooning paradigm. The edge current density in the pedestal is typically dominated by the bootstrap current, which is driven by the steep pressure gradient. However, as a result of current diffusion, the total edge current (sum of bootstrap and Ohmic currents) might evolve on a different time scale than the bootstrap current. In order to determine the effect of current diffusion on the pedestal recovery between subsequent ELM crashes, the inter-ELM evolution of the total edge current density is investigated in this contribution in a wide range of type I ELMy H-modes on JET-ILW.

The effect of current diffusion is assessed by simulating the Ohmic current contribution with the JETTO transport code [5]. Although the resistive timescale is comparable to the ELM period in the investigated pedestals, the simulations show that the Ohmic current is always redistributed inter-ELM so as to mitigate the effect of the varying bootstrap current. As a result, the effect of current diffusion on the time evolution of the total edge current is not significant in the second half of the ELM cycle and does not lead to time delay of the total edge current with respect to the bootstrap current. Therefore, edge current diffusion does not explain why JET-ILW type I ELMy pedestals at high gas rate and high normalised beta are found to be stable to Peeling-Ballooning modes [6].


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(P26) An experimental concept for investigating non-linear microwave interactions in magnetised plasma

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Plasma, as a non-linear medium supporting a rich and diverse range of electromagnetic and electrostatic oscillations, can support a range of multi-wave interactions when excited by multiple injected propagating electromagnetic waves. Electromagnetic wave injection plays a dominant role in the introduction of energy in laser plasma interactions and in the heating of magnetically confined fusion reactors. In magnetically confined plasma, the EM waves tend to fall in the RF to microwave range, whilst in laser plasma interactions the signals are typically near the optical part of the spectrum.

Nonlinear coupling enables energy to be transferred between one or more EM waves interacting in plasma. For example, plasma below one-quarter critical density allows for two injected EM waves to excite an electrostatic Langmuir oscillation, a process known as a Raman interaction, whereas plasma above one-quarter critical density allows for an ion-acoustic oscillation to couple two EM modes, a process known as Brillouin scattering. Coupling of injected EM waves to Langmuir and ion acoustic waves is of interest for a number of laser plasma interactions and in ionospheric physics experiments. Long (and short) pulse signals with normalised intensities approaching those used in some recent laser plasma interactions can be generated using powerful and highly flexible microwave amplifiers. Understanding of the nonlinear electrodynamics will benefit from employing microwave sources and amplifiers to precisely launch and electronically control multiple EM signals. The relatively long lived, benign and accessible plasma relevant to coupling of microwave frequency signals will enable the use of insertion diagnostics in addition to analysing the EM signals.

Other multi-wave interactions can overcome challenges in the delivery of heating and current drive in future magnetic confinement fusion (MCF) reactors. For example, direct heating of the ions may become problematic in future MCF reactors, whilst, in the case of spherical aspect ratio tokamaks, poor access to low cyclotron harmonics of the electrons complicates the delivery of EC heating and current drive. The promise of beat-wave interactions between two microwave signals and the cyclotron motion of the ions and electrons will be investigated, as will the potential for current drive by exciting lower hybrid oscillations by beat-wave interactions and via helicon waves.

To undertake this research a medium-scale linear plasma experiment is being designed. The main section of the plasma will be magnetised at up to 0.08T using a set of quasi-Maxwell coils. The plasma will be created by an RF helicon source, using a whistler wave injected from a high-field region near (or, in inductive mode, below) the lower hybrid resonance, to generate a dense, large, cool plasma with high ionisation fraction (an electron number density up to $10^{19}$m$^{-3}$ has been reported). Helicon sources have attracted interest as a method of generating plasma for industrial processing applications besides their use in fundamental physics research. A range of frequency-flexible microwave sources will provide beams to enable multi-wave coupling experiments. The paper will present the proposed apparatus and will outline the envisioned research programme.

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Pre-clinical evaluation of lethal and sub-lethal DNA damage in cells cultures by ultra-short pulse and ultra-high dose rate laser accelerated protons

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Particle therapy has been cited as an effective treatment modality compared to photons and electrons based therapies for solid tumors located in close proximity to critical organs, such as spinal cord, brain and heart.

Numerous studies have demonstrated the feasibility of using high LET particles in tumor cells; however, the very high installation and operational costs limit the utilization of particle therapy. The idea of future facilities based on laser-driven ion accelerators has been proposed as a way of reducing complexity and cost. Due to the ultrashort duration (10⁻¹² s) of these beams and their consequent ultrahigh dose rates (up to 10⁹-10¹⁰ Gy/s), these beams can potentially deliver lethal DNA damaging dose which tumor cells with unstable genome may fail to repair, whilst normal cells are able to repair the same damage.

Our work, in the context of the A-SAIL (Advanced Strategies for Accelerate Ions with Lasers) project, aims to optimize and validate the dose distribution of laser-driven proton beams at high energies (~ 10 MeV) and to study the effectiveness of these beams in cell lethal and sub-lethal damage induction. We investigated the effects of the laser driven protons on DNA DSB damage, cell survival and stress induced pre-mature senescence (SIPS) in human skin fibroblasts (AG01522) and endothelial cells (HUVEC) in laser facilities based in the UK (Gemini, VULCAN) and France (LULI).

We observed a close similarity between the yields of laser accelerated and conventional clinical proton beam induced DNA DSB damage and SIPS and their enhanced effectiveness compared to low LET radiation (225 kVp X-rays). From cell survival assay, an increased cell killing effect was observed with laser accelerated protons compared to X-rays for doses above 1Gy on samples of both the cell lines. Further comparison experiments with high LET particles from radioactive source (α-particles) have been performed to assess the outcomes. Our results can be used as an input to other tumor cell killing models for further optimization of the laser driven proton therapy in conjunction with DNA repair inhibitors and radioresistant tumors.

Tracking dust in magnum-PSI

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Plasma facing components in magnetic fusion reactors must be resistant to huge power loads and particle fluxes to sustain a burning plasma. Conventionally, the plasma interaction with solid surfaces is considered to cause erosion of the material purely in the form of atoms and molecules, which are rapidly ionised and redeposited on the surface in a cyclic process. For future commercial machines operating for months without shutdown periods, a loss-less re-deposition process must occur at all plasma facing surfaces to prevent damage. The release of micro-scale solid and liquid particles known as dust from surfaces limits the effectiveness of this redeposition [1, 2]. This is because the high mobility of dust leads to local erosion of material, with future devices predicted to produce hundreds of kilogrammes of dust [3]. With safety limits on dust production in place for ITER, dust survivability and transport are issues of critical importance for tokamak operation. Comparison of dust behaviour in small-scale experiments with theoretical models is vital to investigate dynamics and improve physical models.
The dust tracking code DTOKS [5, 6] was used to model dust injection experiments performed at the Magnum-PSI facility in the Netherlands. Artificial tungsten spheres with diameters of 5μm, 9μm and 16μm were released into the hydrogen plasma upstream of the target area. Their motion was tracked with two fast imaging cameras observing optical radiation from thermal emission and reflection. This information was subsequently used to reconstruct their paths. The accuracy of the DTOKS model is reviewed in relation to these results.


(P29) Electrostatic shock to pulse transition in multispecies plasmas
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Collisionless shock waves occur commonly in various plasma environments and are believed to play a central role in phenomena of key interest in astrophysics [1]. Recently, by means of proton radiography techniques, the early stage evolution of electrostatic shock in a tenuous plasma was observed with high temporal and spatial resolution, revealing an interesting phenomenon: a transition from an electrostatic (potential) shock to a pulse structure was observed, upon reconstructing the electric field profile at different times; see Figure [2].

We have recently shown [3], by means of an advanced multiscale perturbation (analytical) technique based on a dissipative Korteweg-de Vries/Burgers type model, that this transition can be attributed to an interplay between dissipation and dispersion mechanisms, in addition to the inherent plasma convective nonlinearity. In this presentation, we investigate analytically and numerically how this transition can be quantitative modelled by parametrized solutions of a generalized Korteweg - de Vries/Burgers type equation. An analytical solution is derived,
representing a mixture of a shock profile and a train of pulses, whose dynamical evolution reproduces the observed waveform.


(P30) Temporal evolution of high Mach number electrostatic shocks in Laboratory plasma

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Collisionless shocks (CS) are relevant to a variety of astrophysical scenarios, such as the generation of highly energetic particles and cosmic rays during supernova explosions, and have recently attracted attention also in several laboratory plasma investigations employing high-power lasers. We present here a study of the generation and evolution of CS in tenuous plasma, carried out at the VULCAN laser at Rutherford Appleton Laboratory. The shocks are generated during the expansion of a warm plasma, produced by the irradiation of a thin solid foil by a long (≈1 ns) and intense (≈10^15 W/cm^2) laser pulse, into a tenuous (≈10^16 cm^-3), non magnetized background plasma. Shock structures are seen to develop at the interface between the two plasmas, which were probed by using a high-resolution proton projection imaging (PPI) technique [1]. The temporal evolution of electrostatic shocks in the ambient plasma was observed and the associated electric field has been reconstructed, identifying a transition from a unipolar field profile, typical of a double layer structure, into a bipolar electric field profile, and the subsequent formation of a collisionless and electrostatic shock [1]. This structure is then seen to propagate in the ambient plasma with a Mach number ≈ 3.5. PIC simulations support the existence of high Mach number (≈3.3) shocks launched by the collision of plasma clouds of equal electron and ion temperatures [3].

A theoretical model taking into account a multi-ion plasma configuration has been shown to explain qualitatively the transition from a unipolar to bipolar electric field pulse as well as, to some extent, the large value of its propagation speed. We have investigated from first principles the relevance of the model to our experimental plasma, also taking into account a weak but finite intrinsic plasma dissipation.


(P31) Carbon ion acceleration from nanometre-thick foils utilising ultra-short laser pulses

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Presented are results of recent experiments using the GEMINI laser at the Rutherford Appleton Laboratory investigating the acceleration of ions from ultrathin carbon foils (2-100nm). The laser delivered ~ 6J on target in a 30fs (λ= 800nm) pulse providing an intensity of approximately 6x10^{20} Wcm^{-2}. A double plasma mirror system was implemented to provide a contrast of 10^{12}.

In this interaction regime, it is known that laser polarization can play an important role in determining the dynamics of the laser-target coupling and of the ion acceleration process [1]. In particular, the use of circular polarization (controlled by a quarter-wave plate) can significantly reduce electron heating, helping to preserve the opacity of the foils during the irradiation. This is key to accessing acceleration regimes where the laser radiation pressure is the dominant mechanism, such as the so-called Light Sail process.

Our results highlight a strong dependence of the maximum ion energies on laser polarisation, with circular polarisation leading to the highest values (>25MeV/nucleon) for carbon and contaminant protons. For targets thinner than 20nm, circular polarisation produced energies over double that of linear polarisation. This is consistent with the onset of Light Sail acceleration, also indicated by Particle in Cell simulations.


(P32) Withdrawn

(P33) Inductive compression and heating of a laser produced plasma

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The results of an experiment on inductive heating and compression of a laser produced plasma (LPP) in vacuum are described. The laser plasma was produced by laser ablation of a copper (Cu) target at 2 J cm^{-2}. A pulsed magnetic field, with an amplitude of 0.3 T and a period of 2.2 μs, was produced by a 3-turn spiral induction coil placed 10 mm above the ablation spot, as shown in Figure 1.

![Image of the experimental setup used for inductive compression and heating of LPP.](image-url)
The ablation plasma flow through a central aperture in the induction coil was measured using a Langmuir ion probe. Time-resolved imaging revealed that the magnetic field caused strong compression of the plasma which flowed through the aperture in the coil, as shown in Figure 2. Heating of the plasma is evidenced by strong enhancement of the overall visible light emission and the appearance of Cu+ line emission. Magnetic compression and plasma heating was also observed in a setup using two induction coils separated by 10 mm. These techniques may find application for enhancing the sensitivity of laser induced breakdown spectroscopy, increasing the ion yield in laser plasma ion sources, or controlling the ablation plume expansion in pulsed laser deposition.

![Figure 2. ICCD images of optical emission at 1.9 μs after laser pulse without (left) and with (right) pulsed magnetic field.](image)

(P34) Withdrawn

(P35) Insights into reactive species delivery and scaling using plasmas produced in high aspect ratio needles

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The development of minimally invasive, non-thermal plasma based treatments for internal cancers and other conditions requires detailed understanding of plasma production and reactive oxygen and nitrogen species (RONS) delivery via high aspect ratio needles or tubes. In order to reach treatment sites within the body, tube lengths of 10’s of cm are required, while in order to remain minimally invasive their radii must be in the order of 1 mm or less. During transport over the length of such systems, the most highly reactive RONS tend to recombine into either; comparatively stable, but still reactive RONS or stable, unreactive molecules, thereby changing the reactivity of the gas reaching the treatment site. As a result,
quantification and optimization of the reactive species delivered through these systems is required in order to achieve optimal outcomes in applications.

In this work, this problem is studied through 0-D plasma-chemical kinetics simulations using a He/H$_2$O plasma chemistry [1] implemented in the *GlobalKin* code [2]. The base case simulation consists of a 20 cm long tube with an inner diameter of 1 mm and a gas flow of 1 slm He containing 5000 ppm H$_2$O. A constant power deposition is applied for the first 3 cm after which the power is switched off. The densities of the dominant neutral reactive species for the base case simulation are plotted as a function of distance from the gas inlet in Fig. 1. The shaded region illustrates the region of power deposition. As expected, all reactive species are found to increase, with differing time constants, during the power-on period. When the power is switched off, the more highly reactive species, O, H and OH, recombine rapidly, again with differing time constants, to stable species over a distance of several cm, while the less reactive, but still biologically relevant species, H$_2$O$_2$ and HO$_2$, remain relatively constant over the remainder of the tube length.

It is found that the reactive species composition of the gas reaching the end of the needle is strongly influenced by the tube radius and length, the gas flow rate, the location of power deposition (start or end of the needle) and whether the power deposition is continuous or pulsed. These changes are mediated by the differing time constants for species production and destruction, and the role of surface recombination [1] and offer opportunities for reactive species tailoring in biomedical applications of these sources.


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(P36) Monitoring and control of plasma based atomic layer processes

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Plasma based atomic layer processes are key technologies for plasma manufacturing with atom-scale precision. These processes often critically rely on surface reactions involving atomic oxygen or atomic hydrogen. Accurate measurements and control of their densities is hence a crucial aspect in the development of future technologies. Two-photon Absorption Laser Induced Fluorescence (TALIF) spectroscopy is a well-established and reliable technique for measurements of absolute atomic oxygen and hydrogen densities. It is experimentally, however, quite involving and hence not well suited for plasma monitoring and control in industrial environments. A simple and easy to implement optical emission spectroscopic (OES) technique is classical actinometry, using small quantified admixtures of rare gases as reference. Its simplified assumptions make it easy to apply, but they also limit its reliability to rough estimations only. A major issue is dissociative excitation and its inherent associated dependence on the mean electron energy. Various advanced actinometry techniques have been developed taking into account dissociative excitation through theoretical predictions of the mean electron energy and recent improvements exploit direct coupling with specifically designed numerical simulations [1]. These approaches have proven to significantly enhance reliability and accuracy. However, they are also quite involving as they require specific simulations for each...
plasma system to be investigated. Alternative more flexible approaches use additional specifically selected optical emission lines to determine the mean electron energy simultaneously through a more sophisticated analysis technique - this technique is often referred to as Energy Resolved Actinometry (ERA) [2, 3, 4]. This presentation will discuss the reliability of this promising approach for monitoring atomic oxygen and hydrogen densities in plasma based atomic layer processes using TALIF measurements as a benchmark.


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(P37) Withdrawn

(P38) Plasma enhanced-pulsed laser deposition: proof-of-concept

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Metal oxide thin films find uses in many modern technologies. Of focus here being Zinc Oxide and Copper Oxides, which can be used in photovoltaics, batteries, electronic pressure sensors, displays and more. An established method of making thin films is Pulsed Laser Deposition, where a pulsed laser ablates material from a target, which then deposits onto a substrate, growing the film. Although PLD is easy and readily used for metal targets, oxide targets have been shown to be much more challenging, with much slower deposition rates and requiring carefully tuned backgrounds to achieve desired stoichiometry. In our work we describe and quantify the differences between the ablation of metal and metal-oxide targets using a 2-dimensional hydrodynamic code, POLLUX. We show that metal-oxide targets ablate approximately 60% less than their metal counterparts with comparable yet slightly cooler ion temperatures. These simulations are benchmarked against the ablation of the same targets under comparable laboratory conditions.

In order to overcome the limitations of metal-oxide PLD, a novel deposition technique has been developed Plasma Enhanced-Pulsed Laser Deposition (PE-PLD), where a metal target is ablated in the presence of oxygen reactive species produced by an Inductively Coupled Plasma (ICP); Allowing for use of the easier ablated metal targets, and stoichiometry control of the deposited film via different operating conditions of the ICP. Copper Oxide and Zinc Oxide films have been deposited by PE-PLD, and analysed by a variety of techniques including TEM, EDX, MEIS and...
others. PE-PLD is shown to deposit films at a comparable rate to traditional PLD, whilst also allowing for control of the films stoichiometry via different oxygen ICP pressures; with 7.5 Pa yielding Cu2O (211), and 13 Pa yielding CuO (020), whereas similar pressures yield wurtzite ZnO. In addition to this, due to the higher on target ion energies, PE-PLD does not require substrate heating, allowing for growth of the same films on polymer substrates. Finally it is shown that additional gases can be introduced into the system, such as nitrogen in order to produce nitride and oxynitride films.

(P39) Investigation of zonal flow stability using spatial averaging
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Zonal flows are of great interest inside magnetically-confined plasmas as their interaction with turbulence may in principle be used to control plasma confinement via processes such as shearing of turbulent eddies due to the alternating nature of the velocities of the zonal flows. Zonal flows are structures with a poloidal wavenumber of zero and a larger radial wavenumber but with plasma flow in the poloidal direction.

The growth of zonal flows from drift modes has been extensively studied and non-linear processes are found to be the driving forces, chiefly 4-wave interactions. The linear decay of zonal flows can be attributed to energy transfer to compressible poloidal oscillations (GAMs) via Landau damping and the non-linear decay can be attributed to a tertiary Kelvin-Helmholtz instability. However, building upon previous work, the linear stability of zonal flows was re-examined using a spatial averaging technique. In particular the spatial averaging was applied to the dispersion relation obtained from the linearised Extended Hasegawa-Wakatani equations. The spatially independent dispersion relation was solved to yield linear growth rates for a small drift wave perturbation against a zonal flow background. The growth rates come from resonance terms which suggests Landau-damping of zonal flows and transfer of energy to drift waves. The growth rates and energy predictions were compared to measurements from a simulation and found to match reasonably well under a certain range of parameters.

(P40) Observing dynamics of electron solvation in H2O during ultrafast pulsed-ion radiolysis
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Understanding the effects of ion interactions in condensed matter has been a focus of research for decades. While many of these studies focus on the longer term effects such as cell death or material integrity, typically this is performed using relatively long (>100 ps) proton pulses from radiofrequency accelerators in conjunction with chemical scavenging techniques [1]. As protons traverse a material, they generate tracks of ionisation that evolve rapidly on femtosecond timescales. Recently, measurements of few-picosecond pulses of laser driven protons have been performed via observation of transient opacity induced in SiO2 with sub-picosecond resolution [2]. Here we present results showing a dramatic difference in the solvation time of electrons generated due to the interaction of relativistic electrons/X-rays and protons in liquid water. The solvation time of these electrons increases from <10 ps for fast electrons and X-rays to >190 ps for the protons. The role of ionisation tracks and subsequent formation of nanoscale cavities in water on the extended recovery time is discussed.

(P41) Relativistic electron beam effects on the hole acoustic instability in degenerate semiconductor plasmas

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In this work we studied the influence of the classical relativistic beam of electrons on the hole acoustic wave (HAW) instability exciting in the semiconductor quantum plasmas. We conducted this study by using the quantumhydrodynamic model of dense plasmas, incorporating the quantum effects of semiconductor plasma species which include degeneracy pressure, exchange-correlation potential and Bohm potential. Analysis of the quantum characteristics of semiconductor plasma species along with relativistic effect of beam electrons on the dispersion relation of the HAW is given in detail qualitatively and quantitatively by plotting them numerically. It is worth mentioning that the relativistic electron beam (REB) stabilises the HAWs exciting in semiconductor (GaAs) degenerate plasma.

(P42) Theoretical issues in modelling ion cyclotron emission associated with transient events in magnetically confined plasmas

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Ion cyclotron emission (ICE) from energetic ion populations, including fusion-born ions, has been detected from most large magnetically confined plasmas, including JET and TFTR DT plasmas. The primary observational signature of ICE is strongly suprathermal emission, with narrow spectral peaks corresponding to successive cyclotron harmonics of the energetic ion species in the emitting region, which is typically the outer midplane edge. Recently ICE has been measured in the LHD heliotron-stellarator, and in the KSTAR tokamak. The ICE data from LHD [1,2] and KSTAR [3] addressed using particle-in-cell (PIC) codes suggests that, as in earlier experiments, the magnetoacoustic cyclotron instability (MCI) is responsible for driving the emission. The MCI arises when there is a spatially localized inversion in velocity space of the energetic ion population. Its properties that replicate ICE observations include, in addition to spectral characteristics, the required scaling with energetic ion concentration [4]. Recent advances in the time resolution of ICRF diagnostics are enabling, in LHD and KSTAR, time-resolved ICE measurements during transient, bursty, plasma events that evolve on microsecond timescales. These present new theoretical challenges, which we summarise here. The transient event can cause rapid evolution of the energetic ion distribution, in both real and velocity space, and of the ambient plasma in which the energetic ion population is embedded. This knowledge must be combined with understanding of the drift orbit excursions of energetic ions, which can be comparable to the system size, and the consequences for the confinement of energetic ions as a function of location, velocity and pitch angle. In addition, ion drift velocities in combination with the wavevector of the excited fields – which is seldom well constrained experimentally – can give rise to frequency shifts. Here we examine how the foregoing physics issues can be integrated into the theoretical basis for PIC code modelling of ICE from transient events in LHD and elsewhere.
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(P43) Effect of exchange correlation potential on dispersion properties of lower hybrid wave in relativistic degenerate plasma

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The propagation characteristics of lower hybrid waves are studied in electron-ion relativistic degenerate plasma considering exchange correlation effect [1]. The quantum hydrodynamic equations [2] are used to obtain the dispersion relation of lower hybrid wave, which is discussed considering three different regimes i.e., non-relativistic, relativistic and ultra-relativistic regime respectively. It is found that the relativistic effects modify the plasma current density and degenerate pressure, thus introduces correction terms in the dispersion relation, which in turn give rise to a new lower hybrid mode. The presence of Bohm force and exchange potential also alter the dispersion properties of lower hybrid waves. In the case, when the number density of electron is of the order $10^{36} \, / \, \text{m}^3$ the relativistic effects can no longer be ignored, while the plasma with number density $10^{39} \, / \, \text{m}^3$ enters into the ultra-relativistic regime. The analytical and numerical results explicitly show the influence of Bohm force, exchange correlation potential, relativistic velocities of electrons and kinetic pressure of ions on the frequency of the lower hybrid wave. The present found its direct relevance for the dense astrophysical environments like white dwarfs and for laboratory fusion plasma experiments [3-5].


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We have observed a broad continuum in the forward directed spectra of a 10 ns Nd:YAG laser operating at 1064 nm in water. The laser is focused to deliver a single pulse into bulk water with sufficient intensity, estimated at $3.5 \times 10^{10} \, \text{W/cm}^2$, to generate optical breakdown within the liquid. In both tap and highly filtered, de-ionized water targets, the spectra observed in the forward direction of the laser exhibit phenomena similar to those described in the literature as super-broadening, super-continuum generation or conical broadening [1,2]. To our knowledge this phenomenon has only previously been observed—whether in water or any other non-linear transparent medium—when femtosecond or picosecond pulses have been used [3,4]. The significance of these and our broadband beams is
that they preserve the same level of spatial coherence and focusability as the input laser beam [20]. The physical picture of super-continuum generation in transparent bulk media is currently understood to be connected to filamentation in the nonlinear media occurring above a certain power threshold, which we exceed in the experiments described here [1,5–8].


(P45) Non-linear dynamics of quantum plasmas: hydrodynamic pressure tensors with kinetic behaviour

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Quantum plasmas can be found in a wide range of systems: degenerate electrons in a metals, inertial confinement fusion plasmas, laser-solid based plasmas, dense astrophysical objects, etc. The dynamics of such systems is usually investigated by means of Quantum Hydrodynamic Models, which offer a computationally cheap alternative to the kinetic approach. Nonetheless, the existing approximations for the kinetic pressure tensor are not able to reproduce correctly not even simple results such as the dispersion relation for linear electrostatic waves in a homogeneous quantum plasma. Such shortcomings have a strong negative impact on the predicting power of the models in non-linear regimes.

Based on kinetic results and single particle behaviour of fermions in intense fields, a novel approximation for the kinetic pressure tensor is derived as density functional. It is tested in numerical simulations of quantum plasmas in intense fields with results comparable with the ones provided by the kinetic methods. Moreover, novel corrections are obtained for the formation and dynamics of solitons and vortices associated with the electron plasma oscillations.

(P46) Assessing the impact of 3D eddy currents on merging compression start-up in ST40

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Tokamak Energy Ltd. is presently commissioning ST40, a relatively small ($R=0.4$m), high toroidal field ($B_T\sim3T$) and high current density ($I_p\sim2MA$) spherical tokamak. The main aims of commissioning were to test all sub-systems and to demonstrate Merging/Compression plasma start-up.

Merging/Compression (MC) [1, 2] start-up is an inductive process where two plasma rings are formed around two internal poloidal field coils, through magnetic reconnection the two plasma rings merge to form a tokamak plasma, this tokamak plasma is then radially compressed further increasing the plasma current. Before any current can be inductively driven a plasma must be formed. Plasma breakdown depends on the number of electrons that collide
with neutral atoms before hitting the vacuum wall. An important parameter in achieving breakdown is the connection length [3] (the distance from a point to the vessel wall). First experimental results show that the externally applied vertical field plays an important role in the merging process and we explore how it effects the connection length.

To sustain the forces incurred in operating ST40, the vacuum vessel is relatively thick and as a result significant eddy currents (up to 700kA) are induced into the vessel during Merging/Compression start-up. Additionally, large toroidally discontinuous ports are situated around the vessel (to accommodate vacuum pumps, cameras, vessel cleaning etc.). The ports cannot be modelled in a 2D analytical model but can have substantial local eddy currents flowing through them which can affect Merging/Compression start-up. To investigate the significance of these 3D effects, a Finite Element Model of the ST40 vessel was created using Ansys and the magnetic field was calculated. Subsequently, the impact of the ports on Merging/Compression start-up was determined by comparing connection lengths of a 2D model with the 3D Ansys model. 3D effects are shown to be important and should be considered when optimising the merging process. Experimentally we have found an optimal magnetic configuration and we will compare this configuration to modelling.
