Programme and Abstract book

46th IOP Plasma Physics Conference

23–26 April 2019
Holywell Park Conference Centre,
Loughborough, UK

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46th IOP Plasma Physics Conference

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46th IOP Plasma Physics Conference

Contents

Programme

Oral programme 3

Poster programme 7

Abstracts

Oral abstracts 8

Poster abstracts 27

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Programme

Tuesday 23 April

11:00	Registration *The Babbage (Low Bay)*
12:00	Lunch
13:00	Welcome *Stephenson Lecture Theatre*
Chair: Ken McClements, CCFE, UK	
13:10	**(Invited) Petawatt class lasers and their plasma applications** Nick Hopps, AWE, UK
13:50	**Ionisation balance in simulations of substellar atmospheres** Alisdair Wilson, University of Glasgow, UK
14:10	**Culham Thesis Prize Winner** **Spectroscopic investigations of detachment on the TCV tokamak** Kevin Verhaegh, University of York, UK
14:50	Refreshment Break
15:10	**(Invited) Electron, ion and neutral heating in radio-frequency electrothermal microthrusters** James Dedrick, University of York, UK
15:50	**Kinetic instabilities in a minimum-B ECR discharge** Olli Tarvainen, STFC, UK
16:10	**Onset of 2D magnetic reconnection in fully and partially ionized plasmas** Gert Botha, Northumbria University, UK
16:30	**Rutherford Prize Talk** **A glass of sea water** William Trickey, University of York, UK
16:50	Posters and Refreshments
19:00	Welcome Reception

Wednesday, 24 April

08:30	Arrival Coffee
Chair: Josie Coltman, AWE, UK	
09:00	**(Invited) Plasma heating and energetic particles in solar flare reconnection** Philippa Browning, University of Manchester, UK
09:40	**Collective absorption of laser radiation in plasma at sub-relativistic intensities** Sviatoslav Shekhanov, ELI-Beamlines, Czech Republic
10:00	**(Invited) The edge of chaos in turbulent plasmas** Ben McMillan, University of Warwick, UK
10:40	Refreshment break
11:00	**(Invited) Vlasov simulations of turbulent electron Bernstein waves and electron heating** David Speirs, University of Strathclyde, UK
11:40	**MAST-U Super-X ELM burn-through simulations** Siobhan Smith, University of York, UK
12:00	**Three applications of basic graph theory to plasma chemistry: network visualization, pathway ranking, and a rudimentary operating condition proposal algorithm** Thomas Holmes, University of Sheffield, UK
12:20	**Laser-plasma Instabilities at ignition-scale:Particle-in-cell simulations of shock-ignition** Alexander Seaton, University of Warwick, UK
12:40	Lunch
13:30	Excursions / Freetime
18:30	Refreshments *Loughborough University: Foyer to Sir David Davies Building DAV0.31*
19:00	**Outreach Public Lecture:** **The Path to Delivering Fusion Power** Ian Chapman, UKAEA, UK Loughborough University: Sir David Davies Building DAV0.31

Thursday, 25 April

08:30	Arrival Coffee
Chair: Ceri Brenner, STFC, UK	
09:00	**(Invited) The Parker solar probe mission** Christopher Chen, Queen Mary University of London, UK
09:40	**Modelling of cryogenic pellet ablation in a hot plasma and the subsequent gas-plasma interaction** Kyle Martin, University of Glasgow, UK
10:00	**3D perturbative MHD stability of Tokamak Plasmas** Michail-Savvas Anastopoulos-Tzanis, University of York, UK
10:20	Refreshment break
10:40	**(Invited) Electromagnetic filamentary structures transporting plasma in the boundary of tokamak devices** Fulvio Militello, CCFE, UK
11:20	**Pseudospark sourced electron beam driven high power millimetre wave sources** Adrian Cross, University of Strathclyde, UK
11:40	**Antimicrobial efficacy of in situ plasma-generated ozone is effective in inactivation of Pseudomonas aeruginosa biofilms in drains and water-submerged surfaces** Declan Diver, University of Glasgow, UK
12:00	IOP Plasma Physics Group AGM
12:30	Lunch/Posters/Exhibitors
Chair: Gregory Daly, Oxford Instruments Plasma Technology Ltd., UK	
14:00	**(Invited) Electromagnetic field generation schemes on high energy and high intensity lasers** Philip Bradford, University of York, UK
14:40	**Characterization and control of a beam-plasma instability downstream of a divergent magnetic nozzle** Scott Doyle, University of York, UK
15:00	**Inflationary stimulated Raman scattering (iSRS) in inhomogeneous plasmas** Selina-Jane Spencer, University of Warwick, UK
15:20	Refreshment break
15:40	**Dust cloud evolution in sub-stellar atmospheres via plasma deposition and plasma sputtering** Craig Stark, Abertay University, UK
16:00	**Pinning down the collisionless microtearing mode** Chen Geng, University of York, UK
16:20	**Debye-Waller for temperature measurement of shock compressed solids** Ashley Poole, University of York, UK
16:40	**Haines Prize Winner** **3D simulations of turbulent plasma mixing in a simplified representation of the tokamak divertor geometry** Nick Walkden, CCFE, UK
17:00	Reception and Exhibition
18:00	Free time
19:00	Conference Dinner *Burleigh Court*

Friday, 26 April

08:30	Arrival Coffee
Chair: Felipe Iza, Loughborough University, UK	
09:00	**(Invited) Plasma methods in CO_2 conversion** Olivier Guaitella, Ecole Polytechnique, France
09:40	**Particle-in-cell simulations of filamentation in laser wakefields** Eva Los, STFC Rutherford Appleton Laboratory, UK
10:00	**Producing shock-ignition like pressure profiles by indirect drive** William Trickey, University of York, UK
10:20	**Generation of non-thermal plasmas over large and complex surfaces** Henrike Jakob, University of Southampton, UK
10:40	Refreshment break
11:00	**(Invited) Reduced and machine learning models in fusion plasma simulations** Sterling Smith, General Atomics, USA
11:40	**Velocity-space redistribution of fast ions during sawtooth crashes in the MAST spherical tokamak observed using fast ion deuterium-alpha spectroscopy** Andrew Jackson, University of Durham, UK
12:00	**(Invited) Towards thermonuclear plasmas: preparations for deuterium-tritium operation with an ITER-like wall in JET** Fernanda Rimini, CCFE, UK
12:40	Lunch and Close

Poster session

The Babbage (Low Bay)

P1. **Thermal conduction in Odin**
Duncan Barlow, University of Warwick, UK

P2. **Novel coatings for transmission electron microscopy sample preparation**
Emma Hookham, Quorum Technologies, UK

P3. **Compact, lightweight, high power mm-wave sources using a pseudospark sourced electron beam**
Jie Xie, University of Strathclyde, UK

P4. **Absolute atomic chlorine density measurements in the effluent of a radio-frequency atmospheric pressure plasma**
Joshua Boothroyd, University of York, UK

P5. **RF compensation in low temperature plasmas**
Matthew Smith, University of Liverpool, UK

P6. **Observations and modelling of ion cyclotron emission observed in JET plasmas during ion cyclotron resonance heating**
Ken McClements, CCFE, UK

P7. **Full orbit calculations of resonance maps for fast particle-driven Alfvénic modes in the MAST spherical tokamak**
Tiantian Sun, Durham University, UK

P8. **High bandwidth FPGA based diagnostics for MAST-U**
Charles Vincent, Durham University, UK

P9. **Assessing the power loss through infrared thermography in MAST**
Matthew Dunn, University of York, UK

P10. **Progress on a helicon plasma apparatus for multifrequency microwave-plasma interactions**
Kevin Ronald, University of Strathclyde, UK

P11. **The Importance of surface tension gradients in plasma-liquid treatments**
Faraz Montazersadgh, Loughborough University, UK

P12. **Generation and amplification of laser modes with higher order polarisation via Raman amplification**
Roaul Trines, STFC Rutherford Appleton Laboratory, UK

P13. **Cusp soliton in piezoelectric semiconductor plasmas**
Amna Fayyaz, Government College University, Pakistan

P14. **Plasma-driven electrochemical reduction of CO_2**
Muhammad Shaban, Loughborough University, UK

P15. **Enhanced fuzzy tungsten growths due to tungsten deposition**
Patrick McCarthy, University of Liverpool, UK

P16. **Plasma cathode electron beam for high-integrity processing**
Andrew Sandeman, Loughborough University, UK

P17. **Plasma-driven epoxidation using an atmospheric pressure plasma jet**
Han Xu, Loughborough University, UK

P18. **Laser spectroscopic characterization of corundum crystal plasma**
Muhammad Hanif, National University of Sciences and Technology, Pakistan

(Invited) Petawatt class lasers and their plasma applications

C Danson and N Hopps

AWE, UK

The use of ultra-high intensity laser beams to achieve extreme material states in the laboratory has become almost routine with the development of the petawatt laser. The journey to ultrahigh power lasers began with the seminal work of Strickland and Mourou [1] with the development of the technique of Chirped Pulse Amplififcation (CPA); for which they were awarded the Nobel Prize for Physics 2018.

Petawatt class lasers have been constructed for specific research activities including: particle acceleration; Inertial Confinement Fusion; radiation therapy and for secondary source generation (X-rays, electrons, protons, neutrons and ions). They are also now routinely coupled, and synchronized to, other large scale facilities including: mega-joule scale lasers; ion and electron accelerators; X-ray sources; and z-pinches.

The field has moved on a long way since the first Petawatt class laser at LLNL in 1998 with over 50 petawatt class lasers currently operational, under construction or in the planning phase [1, 2 & 3]. This talk provides a comprehensive overview of the current status of petawatt class lasers worldwide and details plans for future facilities to move in to the applications arena with higher rep rates, higher powers and a shift towards mid-infrared wavelengths.

[1] Donna Strickland & Gerard Mourou. Compression of Amplified Chirped Optical Pulses, Optics Communications, Vol 56, No 3 (1985)

[2] Colin Danson, David Hillier, Nicholas Hopps & Davd Neely. Petawatt Class Lasers Worldwide. High Power Laser Science and Engineering, Vol. 3, e3 (2015)

[3] National Academy of Sciences, Opportunties in Intense Ultrafast Lasers: Reaching for the Brightest Light (2018)

[4] Colin Danson et al., Petawatt Class Lasers Worldwide – 2018 Review, To be Published.

Ionisation balance in simulations of substellar atmospheres

A Wilson[1], I Dobbs-Dixon[2], C Stark[3], and D Driver[1]

[1]University of Glasgow, UK, [2]New York University, UAE, [3]University of Abertay, UK

There exists ample observational evidence, in the form of X-ray and radio observations, that brown dwarfs and other substellar objects can have high temperature coronas and other atmospheric emissions, such as flares, that are generally associated with the presence of large scale magnetic fields that are advected by the fluid motions of the atmosphere. This happens despite the atmosphere of these objects being cool enough to be electrically neutral and thus not being able to advect the magnetic field, at least when only considering thermal sources of electrons.

Previously, we have shown numerically that it is possible to generate large, non-thermal changes in ionisation fraction from the kinetic energy of bulk flows via the critical velocity ionisation (CVI) effect. This mechanism depends on a small density of seed electrons, a perpendicular seed magnetic field, and the fluid motion exceeding critical velocity that depends on mass the species present. These critical velocities, despite being of the order of km/s, are easily obtained in the atmospheres of large bodies.

Combining this with a 3-dimensional global fluid dynamics circulation model of extra-solar planetary atmospheres, it is possible to calculate both local CVI rates and local thermal recombination rates and thus a non-thermal equilibrium ionisation fraction. In this manner, we demonstrate that locally the equilibrium ionisation fraction can

exceed 0.1 and globally can average greater than 1 part in 10^6. As well as demonstrating a vital link between macro-scale fluid flows (wind) and micro-scale plasma physics we also show that CVI can produce a large enough number of electrons to explain the advection of the magnetic field to the fluid motions of substellar objects.

(Invited) Electron, ion and neutral heating in radio-frequency electrothermal microthrusters

J Dedrick[1], S Doyle[1], A Gibson[1], T Ho[2], R Boswell[2], C Charles[2], and M Kushner[3]

[1]University of York, UK, [2]Australian National University, Australia, [3]University of Michigan, USA

Low power, compact and neutralizer-free propulsion sources are of significant interest for meeting the challenges of space missions with small satellites. Radio frequency (rf) electrothermal plasma thrusters provide enhanced spatial control of power deposition to the propellant. To increase thrust-power efficiency, in this study we investigate the mechanisms for electron, ion and neutral-gas heating in an rf 13.56 MHz electrothermal microthruster operating in argon at 1.4-1.7 Torr plenum pressure. Two dimensional, fluid-kinetic simulations undertaken with the Hybrid Plasma Equipment Model corroborate measurements of the electron-impact excitation rate via phase-resolved optical emission spectroscopy. The relative role of each heating mechanism on the spatially resolved power deposition is investigated across the alpha-gamma mode transition and pressure gradient on-axis. Prospects for achieving enhanced control of the sheath dynamics, ion-power fraction, neutral-gas heating and thrust via “tailored” voltage waveforms composed of multiple harmonics are discussed.

We wish to acknowledge financial support from EPSRC (EP/M508196/1). The participation of M. J. Kushner was supported by the US National Science Foundation and the US Department of Energy Office of Fusion Energy Science.

Kinetic instabilities in a minimum-B ECR discharge

O Tarvainen[1], I Izotov[2], V Skalyga[2], A Shalashov[2], E Gospodchikov[2], D Mansfeld[2], T Kalvas[3], H Koivisto[3], J Komppula[3], R Kronholm[3], J Laulainen[3], and V Toivanen[3]

[1]STFC Rutherford Appleton Laboratory, UK, [2]IAP RAS, Russia, [3]University of Jyvaskyla, Finland

Kinetic cyclotron instabilities are observed in a wide range of naturally occurring plasmas e.g. radiation belts, planetary magnetospheres, solar coronal loops and flare stars as well as in laboratory plasmas. We report the results of a laboratory experiment on a 14 GHz minimum-B electron cyclotron resonance ion source where the instabilities can be controlled by adjusting the discharge parameters and studied with complimentary diagnostics probing the plasma microwave emission dynamics, x-ray bursts and end losses of both the electrons and highly charged ions [1, 2]. In our experiment the kinetic cyclotron instability of the extraordinary wave of weakly inhomogeneous magnetized plasma is driven by the anisotropic electron population.

It is shown that the repetition rate of the periodic instabilities increases with the magnetic field strength and microwave power and decreases with increasing neutral gas pressure, the magnetic field strength being the most critical parameter determining the threshold between stable and unstable discharge regimes. The temporal dynamics of the microwave emission, energy-resolved electron end losses and fluctuations of the plasma potential are presented. It is also demonstrated that the instabilities can be suppressed by providing injecting microwave power simultaneously at two frequencies sustaining the discharge [3]. Furthermore, we report the first experimental evidence of a controlled transition from the generation of periodic bursts of electromagnetic radiation into a continuous-wave regime of a cyclotron maser formed in the non-equilibrium ECR plasma [4, 5]. Finally, the implications of the kinetic instabilities on the production of high charge state ions with high-frequency minimum-B ECR ion sources are discussed.

The aim of the presentation is to present experimental results and to demonstrate the versatility of our setup in studying the fundamental properties of kinetic instabilities in magnetized discharges, applicable for a variety of naturally occurring and laboratory plasmas.

[1] O. Tarvainen, I. Izotov, D. Mansfeld, V. Skalyga, S. Golubev, T. Kalvas, H. Koivisto, J. Komppula, R. Kronholm, J. Laulainen and V. Toivanen, Plasma Sources Sci. Technol. 23, 025020, (2014).
[2] I. Izotov, O Tarvainen, D Mansfeld, V Skalyga, H Koivisto, T Kalvas, J Komppula, R Kronholm and J Laulainen, Plasma Sources Sci. Technol. 24 045017, (2015).
[3] V. Skalyga, I. Izotov, T. Kalvas, H. Koivisto, J. Komppula, R. Kronholm, J. Laulainen, D. Mansfeld and O. Tarvainen, Phys. Plasmas 22, 083509 (2015).
[4] A. G. Shalashov, E. D. Gospodchikov, I. V. Izotov, D. A. Mansfeld, V. A. Skalyga and O. Tarvainen, Phys. Rev. Lett. 120 (15), 155001, (2018).
[5] A. G. Shalashov, E. D. Gospodchikov, I. V. Izotov, D. A. Mansfeld, V. A. Skalyga and O. Tarvainen, Eur. Phys. Lett., 124, 35001 (2018).

Onset of 2D magnetic reconnection in fully and partially ionized plasmas

G Botha[1], B Snow[2], J McLaughlin[1], and A Hillier[2]

[1]Northumbria University, UK, [2]University of Exeter, UK

2D reconnection is studied numerically in the context of various atmospheric layers in the Sun: the fully ionized coronal plasma; the partially ionized chromospheric plasma; the almost-neutral photospheric plasma. Numerical simulations solve the compressible, resistive magnetohydrodynamic equations, using the one-fluid description expanded to include partial ionization. Reconnection is triggered by driving external flows perpendicularly towards an equilibrium Harris current sheet. The reconnection state is reached for all atmospheric regimes, with the inflow velocity controlling the rate of flux entering the reconnection region. A low plasma-beta enhances reconnection (in the corona) while for higher plasma-beta values (in the chromosphere and photosphere) reconnection occurs only when the inflow approaches the local Alfven velocity. In addition, ambipolar diffusion alters the structure of the current density in partially ionised plasmas.

(Invited) Plasma heating and particle acceleration by magnetic reconnection in solar and stellar flares

P Browning

University of Manchester

Solar flares are dramatic releases of stored magnetic energy in the solar corona, with signatures across the electromagnetic spectrum due to plasma heating and high-energy electron and ion beams. It is widely accepted that energy is released through the process of magnetic reconnection, but many questions remain.

I will describe modelling of confined solar flares in twisted magnetic flux ropes. First, energy release in individual flux ropes will be discussed, in which magnetic reconnection is triggered in the nonlinear phase of the ideal kink instability. Using 3D magnetohydrodynamic simulations coupled with a guiding-centre test-particle code, it will be shown how magnetic reconnection in fragmented current structures can both heat plasma and accelerate charged particles, creating populations of non-thermal electrons and ions as observed in flares. Forward modelling of the observational signatures of this process in EUV, hard X-rays and microwaves will be described, and the potential for observational identification of twisted magnetic fields in the solar corona discussed.

Then, coronal structure with multiple twisted threads will be considered, showing how instability in a single unstable twisted thread may trigger reconnection with stable neighbours, releasing their stored energy and causing an

"avalanche" of heating events, with important implications for solar coronal heating. This avalanche can also accelerate electrons and ions throughout the structure.

Many other stars exhibit flares, and I will discuss some recent work on modelling radio emission in flares in young stars (T Tauri stars). In particular, the enhanced radio luminosity of these stars relative to scaling laws for the Sun and other Main Sequence stars will be discussed.

Collective absorption of laser radiation in plasma at sub-relativistic intensities

S Shekhanov[1,2], Y Gu[1,2], O Klimo[1,3], P Nicolai[4], S Weber[1,2], and T Vladimir[1,4]

[1]ELI Beamlines, Czech Republic, [2]Academy of Sciences of the Czech Republic, Czech Republic, [3]Czech Technical University in Prague, Czech Republic, [4]University of Bordeaux, France

Processes of laser energy absorption and electron heating in an expanding plasma in the range of irradiances $I\lambda^2 = 10^{15} - 10^{16}$ $W\mu m^2/cm^2$ are studied with kinetic simulations. The results show a strong reflection due to the process of stimulated Brillouin scattering and a significant collisionless absorption related to the process of stimulated Raman scattering near and below the quarter critical density. It is complemented with the parametric decay instability and resonant excitation of plasma waves near the critical density. All these processes result in excitation of high amplitude electron plasma waves and electron acceleration. The spectrum of scattered radiation is significantly modified by secondary parametric processes, which provide information on the spatial localization of nonlinear absorption and hot electron characteristics. The considered domain of laser and plasma parameters is relevant for the shock ignition scheme of inertial confinement fusion.

(Invited) The edge of chaos in turbulent plasmas

B McMillan

University of Warwick, UK

As well as linear instabilities, plasmas in general can proceed to unsteady behaviour (generally called turbulence for want of a better word) through finite-amplitude instabilities. These is a particularly important process in sub-critical or meta-stable configurations, where the symmetrical background state is linearly stable, but a large enough push is enough to trigger sustained nonlinear dynamics, like in a row of dominos. An obvious question is how big a push is required in these systems. A related question: what is the boundary between the region of configuration space that decays back to the laminar (equilibrium) state and the turbulent regime? This is called the 'edge of chaos': the behaviour there resembles the overall turbulence state but is considerably simpler. In particular, in certain turbulence simulations, there are propagating features on this 'edge' that strongly resemble the avalanche-like bursts and propagating features seen in many turbulence simulations. Instead of a mess of turbulent features interacting with each other, we are seeing a clean nonlinear process resembling a soliton. These simple structures are qualitatively the same in massive gyrokinetic simulations as a 1D fluid turbulence toy-model, and the underlying processes allowing a nonlinear quasi-steady state are relatively simple. Indeed the existence of such 'relative periodic orbits' in turbulent systems is an important recent discovery in the study of neutral fluids, and plasma models show many of the same features. This gives us some hope that at least certain aspects of strong turbulence in plasmas may be understood systematically.

(Invited) Vlasov simulations of turbulent electron Bernstein waves and electron heating

D C Speirs[1], B Eliasson[1], and L Daldorff[2,3]

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

The coupling of energy from electromagnetic (EM) waves to electron Bernstein (EB) waves, upper-hybrid (UH) and lower-hybrid (LH) waves is of critical relevance to many plasma environments, ranging from the terrestrial ionosphere [1] to magnetic confinement fusion plasmas [2]. Recent experiments using ground-based RF heating facilities such as HAARP [3] have launched L-O mode pump waves into the ionospheric F-region, resulting in the induced formation of magnetic field-aligned density striations within the ionospheric plasma [3] and the observation of descending artificial ionospheric layers (DAILS) [4,5]. The formation of striations and DAIL enhancements are observed in association with lower and upper-hybrid turbulence and significant electron heating within the striation volume. In the current context, the results of 2D numerical simulations are presented using a Vlasov-Maxwell code [6] to study the mode-conversion / coupling of an L-O mode pump wave to trapped upper-hybrid wave eigenmodes of a magnetic field aligned density striation. Different resonant wave-coupling regimes are studied with reference to harmonics of the electron-cyclotron frequency, with multi-wave parametric decay observed leading to lower-hybrid turbulence and high amplitude electron Bernstein waves that (once exceeding the threshold amplitude for stochasticity) can result in significant electron heating. Electron temperatures of >8000K have been obtained in simulation that are sufficient to initialise the formation of suprathermal electron tails as a precursor to generating descending artificial ionospheric layers (DAILS).

[1] S. M. Grach et al., Phys.-Usp. 59, 1091 (2016).
[2] V. Shevchenko et al., Fusion Sci. Technol. 52(2), 202–215 (2007).
[3] G..M. Milikh et al., Geophys. Res. Lett. 35, L17104 (2008).
[4] T. Pederson et al., Geophys. Res. Lett. 36, L18107 (2009).
[5] E. Sergeev et al., Phys. Rev. Lett. 110, 065002 (2013).
[6] B. Eliasson, Transp. Theory Stat. Phys. 39, 387-465 (2010).

MAST-U Super-X ELM burn-through simulations

S Smith[1], S Pamela[2], M Hoelzl[3], G Huijsmans[4], A Kirk[2], D Moulton[2], A Thornton[2], and H Wilson[1,2]

[1]University of York, UK, [2]CCFE, UK, [3]Max Planck Institute, Germany, [4]CEA, UK

Edge localised modes (ELMs) are periodic plasma eruptions that result in high heat fluxes to material divertor targets, which future fusion devices will not be able to withstand [1]. The MAST-U tokamak will test a solution to reduce the steady state heat fluxes - the new Super-X divertor. This divertor has an increased magnetic field line connection length, magnetic flux expansion and is designed to retain neutrals for divertor heat-flux mitigation [2]. The effect on ELMs in the new magnetic configuration is unknown; the first predictions are presented here for ELMs in MAST-U plasmas using the nonlinear MHD code JOREK [3], which is being actively validated against current experiments [4]. The wall-extended grid is merged with the JOREK neutrals model [5] to investigate ELM dynamics in MAST-U. The ELM causes the plasma to burn-through the neutrals front (Fig. 1), the neutrals are ionised and heat flux increases at the targets. Simulation results show a significant reduction in the heat flux to the outer target of the Super-X in comparison to a conventional MAST divertor configuration. The peak heat flux during the ELM is 2 MW/m^2. A study of how ELMs burn-through the neutral gas in the new Super-X configuration is performed and the role of neutral pressure in the divertor is analysed. The simulations are based on validation against MAST data and the neutrals model is compared to SOLPS [6].

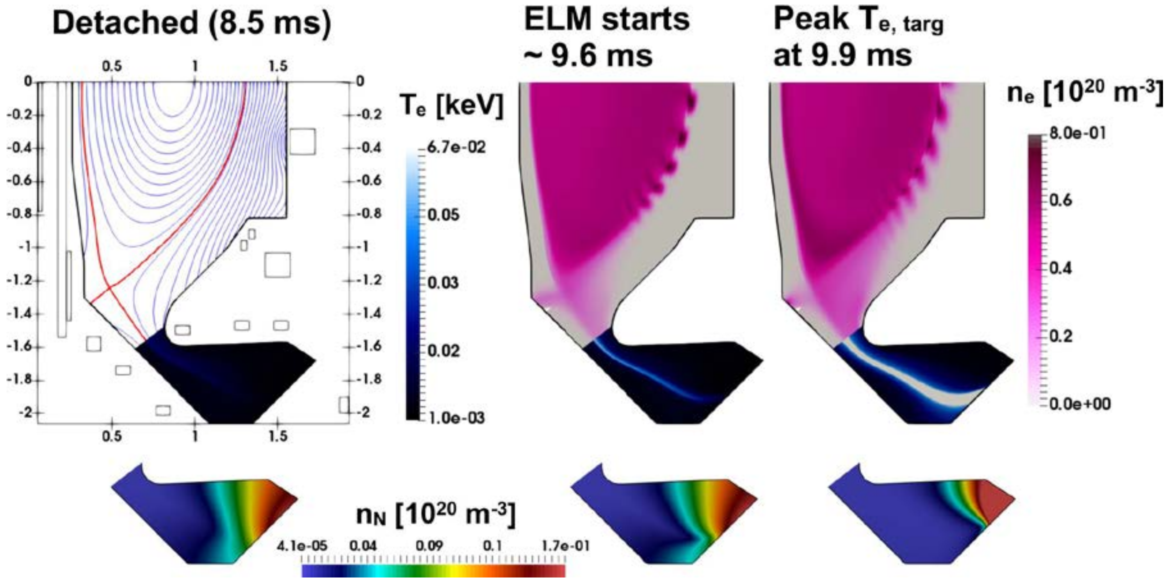

Fig. 1: Electron temperature, density and neutral density; the plasma is detached and burns through during the crash.

[1] R.A. Pitts et al., Journal of Nuclear Materials 438, S48-S56, (2013)
[2] I. Katramados et al. Fusion Eng. Des. 86 (2011) 1595–1598
[3] G.T.A. Huysmans and O. Czarny, Nucl. Fusion 47 (2007) 659–666
[4] S.J.P. Pamela et al., Nucl. Fusion 57 076006 (2017)
[5] A. Fil et al., Physics of Plasmas 22, 062509 (2015)
[6] E. Havlíčková et al., Plasma Phys. Control. Fusion **57** (2015) 115001

Three applications of basic graph theory to plasma chemistry: network visualization, pathway ranking, and a rudimentary operating condition proposal algorithm

T D Holmes[1,2] and W Zimmerman[1,2]

Perlemax Limited, UK, University of Sheffield, UK

The interest in using plasmas for chemistry is increasing. However, plasma chemical kinetic reaction datasets for plasma chemistry simulation are also increasing in size and complexity as they endeavour to more precisely simulate reality. This trend will most likely continue as attempts are made to use plasmas for more complex chemical processes. The inevitable increase in the numbers of possible variables involved mean that complete computational parametric sweeps over all possible ranges, even in 0D conditions, will become exponentially more time consuming, and therefore impractical to as a means of identifying potential optimal conditions for a desired outcome. The probability of identifying potential new plasma chemistry aside from that relating to the target chemicals may also decrease as a consequence. Any additional technique capable of gaining new insights from such datasets would therefore be worth investigating.

This work investigates how basic graph theory might be further applied to assist in solving problems relating to the engineering of plasma chemistry, given its current application to systems of complex interrelated entities. The preliminary findings comprise of three potential techniques:

The first is the utilisation of a network visualization method in a plasma chemical kinetic reaction dataset, suggesting a convenient approach to how large numbers of potential plasma reaction pathways can be simultaneously visualized and compared. The second technique applies Dijkstra's shortest path algorithm to identify

the most probable reaction pathways between each individual chemical species, potentially a means of ranking probabilities of creation and destruction of all the species in the reaction dataset.

The third technique is a rudimentary algorithm operating on a directional graph of the chemical kinetic scheme to return estimations principally for the ideal required electron energy at each approximate stage of the plasma chemical reaction scheme for the formation of a target species, as well as conditions and other species most desirable at each temporal stage. The algorithm is limited to certain constraints and assumptions, but initial outputs suggest that further development could be a step toward improving the chemical selectivity of plasmas.

Laser-plasma Instabilities at Ignition-Scale:Particle-in-Cell Simulations of Shock-Ignition

A Seaton and T Arber

University of Warwick, UK

In the shock-ignition (SI) approach to direct-drive inertial confinement fusion (ICF) a high-intensity laser pulse is used to drive a converging shock through a pre-compressed direct-drive target to achieve ignition. Studies over the last decade have indicated that laser-plasma instabilities (LPIs) play a key role in determining the effectiveness of this ignitor shock. In particular, the hot electron distribution produced by LPIs is vital; electrons with energy over ~100keV may preheat the target ahead of the shock, while those of lower energy deposit their energy in the dense shell behind it and enhance its strength.

Modelling these instabilities is challenging due to the disparity in length and time-scales over which experiments take place and those on which LPIs develop. Furthermore, the behaviour of LPIs depends on detailed kinetic physics, necessitating the use of computationally expensive simulation methods.

Here we present 2D particle-in-cell simulations of a series of simulations of large-scale coronal plasmas. These have been performed with coronal plasma parameters relevant to the OMEGA laser (40kJ) and the NIF (1.5MJ). We discuss the growth and saturation of the instabilities involved and characteristics of the outgoing hot-electron distributions.

This work was funded by EPSRC and CCPP. We acknowledge the use of Athena at HPC Midlands+, the Cirrus UK National Tier-2 HPC Service and the Plasma HEC Consortium supercomputing resources, funded respectively through EPSRC grants EP/P020232/1, EP/P020267/1 and EP/L000237/1. The Cirrus HPC service is also part funded by the University of Edinburgh.

(Public Lecture) The path to delivering fusion power

I Chapman

UKAEA, UK

Fusion power could be one of very few sustainable options to replace fossil fuels as the world's primary energy source. Fusion offers the potential of predictable, safe power with no carbon emissions, and fuel sources lasting for millions of years. However, it is notoriously difficult to achieve in a controlled, steady-state fashion. The most promising path is via magnetic confinement in a device called a tokamak. A magnetic confinement fusion (MCF) power plant requires many different science, technology and engineering challenges to be met simultaneously. This requires an integrated approach from the outset; advances are needed in individual areas but these only bring fusion electricity closer if the other challenges are resolved in harmony. UKAEA has developed a wide range of skills to address many of the challenges and hosts the JET device, presently the only MCF facility capable of operating with both the fusion fuels, deuterium and tritium. Recently several major new UKAEA facilities have been funded and some have started operation, notably a new spherical tokamak (MAST Upgrade), a major robotics facility (RACE),

and a materials research facility (MRF). Most recently work has started on the H3AT (Hydrogen-3 Advanced Technology) centre for tritium technology and a group of Fusion Technology Facilities (FTF). This talk will describe how UKAEA is supporting UK industry and academia to address the key challenges on the path to delivering fusion power and look ahead towards the design of a compact, fusion reactor, STEP (the Spherical Tokamak for Energy Production).

(Invited) The Parker solar probe mission

C Chen

Queen Mary University of London, UK

On 12th August 2018, NASA launched Parker Solar Probe (PSP) - a spacecraft to make in situ and remote observations of the plasma in the inner heliosphere. On 6th November 2018, PSP reached a distance of 35.7 solar radii from the Sun, twice as close as any previous mission, and in the coming years it will get even closer, reaching 9.86 solar radii in 2024, becoming the first spacecraft to fly through the solar corona. In this talk I will describe the mission and science goals of PSP, which include understanding coronal heating and solar wind acceleration, with a focus on what we will learn about basic plasma processes such as plasma turbulence, kinetic instabilities and particle energisation. If available at the time, I may also present some initial results from the first orbit of the mission.

Modelling of cryogenic pellet ablation in a hot plasma and the subsequent gas-plasma interaction

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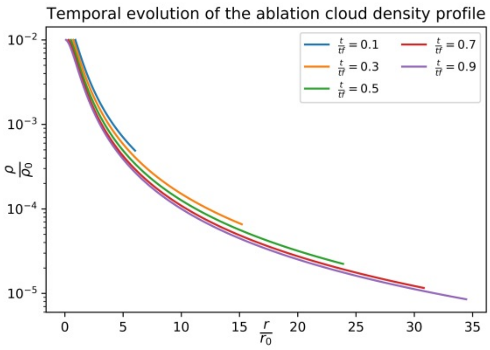
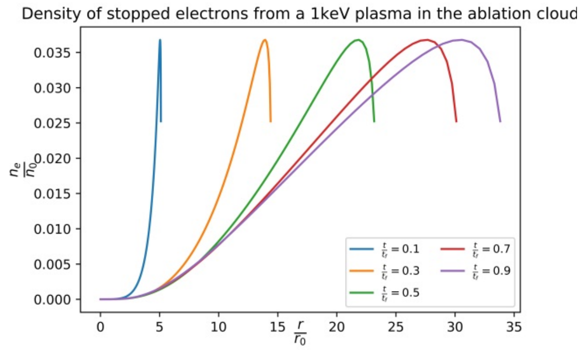
University of Glasgow, UK

The proposed refuelling mechanism for future generation fusion reactors, namely ITER, will be pellet injection: the release of a high velocity deuterium pellet in to the tokamak chamber during operation. Once injected, the tokamak plasma will deposit energy on the pellet, releasing material to form an encasing neutral gas cloud that impedes further ablation. The temporal and spatial evolution system with complex interactions between gas and plasma could have unique signatures that can diagnose properties of the system. We present a holistic model based on a comparison to an evaporative process by conserving mass flux from the pellet to the cloud and by prescribing a density profile to the cloud we can determine the cloud's physical size [1, 2]. Using these properties of the cloud and by applying a variant of the Bethe stopping power formula to the system we can also explore the loss of energy from the charged particles as they traverse the dense gas [3]. We have studied the stopping of charge within the ablation cloud, the energy deposition and charge density to better understand how the cloud inhibits ablation. Many other phenomena may now be studied such as electrostatic interactions and hydrodynamic instabilities owing to density gradients of charged and neutral particles.





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3D Perturbative MHD Stability of Tokamak Plasmas

M Anastopolos-Tzanis[1,2], B Dudson[1], C Ham[2], C Hegna[3], P Snyder[4], and H Wilson[1,2]

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H-mode tokamak plasmas are characterised by quasi-periodic instabilities called edge localised modes (ELMs), which transfer particles and heat to plasma facing components and the divertor of the tokamak device. Large scale reactors, like ITER, will not be able to cope with the corresponding heat fluxes and so active ELM control methods are required. One promising method applies external non-axisymmetric resonant magnetic perturbations (RMPs) and it has been experimentally demonstrated that ELM mitigation or even complete ELM suppression is possible. This work focuses on understanding the impact of the resulting 3D geometry on the ideal MHD stability of the tokamak plasma. The geometry symmetry breaking leads to the coupling of distinct toroidal MHD modes that allows the exchange of energy between them even in the linear phase, altering the growth rate of unstable peeling-ballooning modes which are believed to be the cause of ELMs. Qualitatively, depending on the axisymmetric growth rate spectrum a particular mode can be either stabilised or destabilised. Although, a definite trend exist for extrema in the spectrum. Minima are observed to be always stabilised, while maxima are observed to be always destabilised. In order to quantitatively examine the impact of mode coupling, perturbation theory is employed to calculate correction terms in growth rate and mode structure, since the applied field is orders of magnitude lower than the main axisymmetric confining equilibrium field. Perturbation theory requires information from the full non-axisymmetric plasma equilibrium and the axisymmetric toroidal modes that form a basis for the 3D mode. As such a numerical framework is constructed based on the axisymmetric stability code ELITE, to obtain the plasma response and the toroidal basis functions in order to calculate the change in the linear growth rate spectrum resulting from a given RMP configuration. It is observed that a resonant edge perturbation leads to large plasma response, which in turn leads to significant modification of the MHD spectrum above a certain amplitude of the applied field.

Acknowledgements
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/P012450/1]. 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. This research is also supported in part by the U. S. Department of Energy (DOE) Office of Fusion Energy Sciences under grant no. DE-FG02-86ER53218.}

(Invited) Electromagnetic filamentary structures transporting plasma in the boundary of tokamak devices

F Militello[1,2], D Hoare[1,3], J Omotani[1], Fabio Riva[1], S Newton[1], T Nicholas[1,4], D Ryan[1], and N Walkden[1]

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The formation of filamentary structures is observed in space, solar and experimental plasmas. The plasma in the boundary region of magnetic confinement devices provides a good example of this general phenomenon, as the plasma is transported towards the solid surfaces of the machine by means of elongated, field-aligned coherent structures which resemble filaments. These perturbations erupt from the well-confined region of the machine and carry a significant amount of hot and dense plasma, potentially harmful for the plasma-facing components, through a rarefied and relatively cold environment. Historically, filament dynamics has been treated using an electrostatic approximation. However, reactor-relevant plasmas will have sufficiently high pressure, even in their boundary regions, that the plasma beta (the ratio of thermal to magnetic pressure) will be high enough to violate the electrostatic approximation. The electromagnetic effects associated with the filaments in the boundary plasma has been investigated by performing numerical simulations of isolated filaments bounded at both ends in the parallel direction by two perfectly-conducting material surfaces. Depending on the plasma beta and the plasma conditions, two asymptotic regimes were identified: an electrostatic regime where the magnetic field is unaffected by the motion of the filament and vice-versa and a more interesting electromagnetic regime where the magnetic field lines are frozen into the plasma. In this last case, filaments have higher outward velocities in their center and are slower close to the point at which they meet the material surfaces. This differential velocity arises because the perturbation of the electrostatic potential responsible for the filament motion decouples from the one generated at the entrance of the Debye sheath, where line-tying becomes important. At intermediate beta, the filaments enter a regime in which the field lines are only partially frozen but significantly perturbed, creating electromagnetic fuzz around the separatrix of the machine. Electromagnetic effects include bending of the plasma filaments, braiding of the magnetic field lines and, potentially, magnetic reconnection induced by the filament motion, which are all quantified as a function of the plasma beta (see Fig.1 for an example of an electromagnetic filament). The electromagnetic effects are found to have a significant impact with values of beta of a few percent, within the range expected in future and present fusion devices. This behavior is modelled under rather general conditions, and might therefore also be applicable to other fields of plasma physics, such as, for example, solar coronal loops.

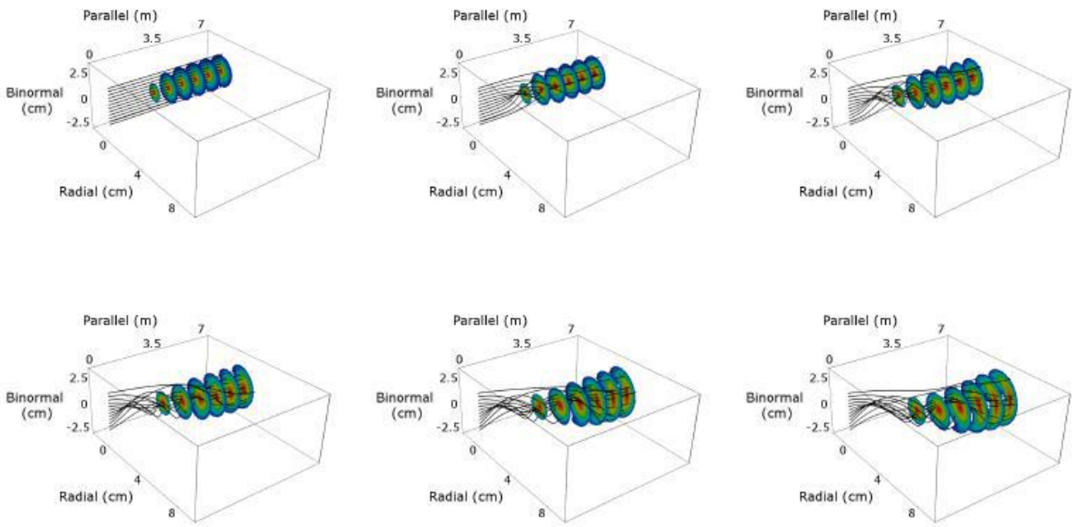

Fig. 1: (a) Field line twisting associated with a filament motion, each panel corresponding to a 4 micro-seconds increase in time. The colourplot represents the cross section of the plasma density in the filament (only half of the parallel domain is represented).

Antimicrobial efficacy of in situ plasma-generated ozone is effective in inactivation of Pseudomonas aeruginosa biofilms in drains and water-submerged surfaces

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A reduction in biofilm bioburden is demonstrated using in situ cold-plasma-generated ozone, showing that this practical technique has potential for decontaminating inaccessible periodically wetted surfaces. The method ionizes the ambient air to produce the ozone (and other radicals) without presenting a general environmental hazard. A key advantage of using a gaseous biocide over a liquid one is the former's ability to penetrate small-scale surface features without being restricted by surface tension limitations. Drains that harbour biofilms on interior surfaces can be decontaminated effectively by the plasma system: the drain inlet is covered and sealed by the device itself, and the water trap completes the seal on the outlet. The levels of ozone generated are sufficient to reduce significantly the bioburden in biofilms, even when such biofilms are partially or wholly submerged in water. Additionally, we show that such ozone treated surfaces do not promote biofilm re-growth. Biofilms in drains, known to be resistant to conventional liquid chemical surface cleaning, can pose a serious health challenge in critical environments. The demonstrated efficacy of the technique presented here in such contexts commends the method for effective cleaning of not only drains, but other biofilm-prone surfaces, including sanitary ware and medical devices.

(Invited) Electromagnetic field generation schemes on high energy and high intensity lasers

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High power, high intensity lasers ($I > 10^{15}$ Wcm^{-2}) can generate enormous currents in solid targets, with discharges reaching mega-ampere levels on some petawatt laser systems. The effect of these currents is to produce electromagnetic fields, ranging from transient electromagnetic pulses (EMP) to intense, quasi-static fields.

EMP in the megahertz and gigahertz regimes are a well-known by-product of laser-matter interactions and they have dogged high power laser experiments since their inception in the 1980s. Laser-driven EMP can seriously degrade scientific measurements and damage electronic equipment, entering coaxial cables, oscilloscopes and even the mains voltage supply at several metres from the target chamber. Though the physics of EMP has not yet been fully explained in all intensity regimes, it is known to be more powerful at higher laser intensity. It depends on the ejection of hot electrons from the laser target, which leave behind a positive potential that discharges through the target support. The oscillation of this current across the support then induces dipole antenna emission at gigahertz frequency. Efforts to mitigate the effects of EMP have hinged on three different approaches: (i) Modification of the target to reduce electron emission (e.g. by reducing the target dimensions) (ii) Modification of the target support to suppress the discharge current (iii) Shielding measurement equipment using Faraday cages or by enclosing the target in a metal box.

A developing application of laser-driven currents is in generating magnetic fields of picosecond-nanosecond duration with magnitudes up to ~600 T. Single loop and helical coil targets can direct the discharge currents along wires to generate spatially-uniform, quasi-static magnetic fields on the millimetre scale. These magnetic fields can then be used to engineer states of highly-magnetized matter, such as those only found in tokamaks, white dwarfs, radio pulsars and future high-performance inertial confinement fusion implosions.

Characterization and control of a beam-plasma instability downstream of a divergent magnetic nozzle

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The formation of double layers (DL) in expanding plasma sources is of interest to fundamental aspects of magnetic nozzles and can be applied to electrodeless, charge neutral, scalable propulsion systems such as the low pressure, radio frequency (rf) helicon double layer thruster (HDLT). The Chi Kung experiment from which the HDLT is derived, employs a diverging magnetic field geometry to generate an electric double layer, accelerating ions on-axis and producing a collimated ion beam which expands into a larger volume/chamber. The interactions between this beam and plasma downstream of the double layer can give rise to instabilities through resonant effects, such instabilities are undesirable as they introduce power loss mechanisms. In this work electrostatic probes were employed to measure a 4-20 kHz instability in the ion saturation current downstream of an electric DL. The magnitude of the instability was found to vary linearly with the applied rf power (100-600 W) and background argon pressure (0.2-0.8 mT) and varied super-linearly with the applied solenoid current (2-8 A). A spatially resolved characterisation of the instability magnitude downstream of the DL determined maxima at the beam-background interface, indicating a density or velocity gradient driven instability. The evolution of the instability frequency and amplitude were observed with an imposed sinusoidal ion sound wave, altering the beam-background density gradient and consequentially also the growth rate. The introduction of an ion sound wave was achieved through the application of a variable kHz rf amplitude modulation to the 13.56 MHz power supply. Through the application of rf amplitude modulations in the frequency range 2-12 kHz the magnitude of the instability was reduced by up to 60%, with higher frequency rf modulations achieving a greater reduction at a lower rf modulation amplitudes. Spatially resolved measurements of the ion energy distribution function (IEDF) confirmed that the ion beam was not adversely affected by the applied rf modulation. The application of this technique advances understanding of the growth conditions of resonant instabilities in magnetised plasmas and provides a control mechanism for potentially disruptive instabilities.

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Inflationary Stimulated Raman Scattering (iSRS) in inhomogeneous plasmas

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University of Warwick

In inertial confinement fusion (ICF) plasmas, laser-plasma instabilities (LPIs) act to reduce the efficiency and symmetry of target compression by scattering potentially large amounts of the incident laser energy, and by producing hot electrons which can deleteriously pre-heat the target. Stimulated Raman Scattering (SRS) is a three-wave parametric instability which involves the interaction between an electron plasma wave (EPW), laser light, and a scattered light wave. SRS has an upper density bound at the quarter critical density of the coronal plasma, and its growth is further constrained by large linear Landau damping at densities much below the quarter critical [1]. However, experiments on the Trident laser system have observed enhanced laser reflectivities from SRS at densities for which the linear theory predicts the Langmuir wave will be too strongly Landau-damped for SRS to grow [2].

This enhanced reflectivity occurs once the laser intensity exceeds some threshold value, and is known as inflationary SRS (iSRS), since the reflectivity due to SRS rises immediately by several orders of magnitude once this threshold is surpassed. Since these observations, the theory of iSRS has been developed primarily in simulations of the effect in homogeneous plasmas; focussing on reduced Landau damping due to kinetic effects [3]. The proposed non-linear mechanism by which iSRS occurs is electron-trapping in the driven EPW, and therefore fully kinetic particle-in-cell (PIC) simulations have been used to extend the study of iSRS [4].

In this work we take as a starting point the extensive literature on iSRS in homogeneous plasmas for indirect-drive ICF, and use PIC simulations to probe how iSRS develops in plasmas with a density gradient, such as those that will be present in shock-ignition direct-drive ICF schemes. In this talk, we will present results of the first simulations of iSRS in inhomogeneous plasmas with NIF-relevant parameters and scale-lengths. An increased understanding of the link between coronal density scale-lengths and reflectivity due to SRS and iSRS is of significant interest to the development of shock-ignition ICF schemes.

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Dust cloud evolution in sub-stellar atmospheres via plasma deposition and plasma sputtering

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In contemporary sub-stellar model atmospheres, dust growth occurs through neutral gas-phase surface chemistry. Recently, there has been a growing body of theoretical and observational evidence suggesting that ionisation processes can also occur. As a result, atmospheres are populated by regions composed of plasma, gas and dust, and the consequent influence of plasma processes on dust evolution is enhanced.

This paper aims to introduce a new model of dust growth and destruction in sub-stellar atmospheres via plasma deposition and plasma sputtering.

Using example sub-stellar atmospheres from DRIFT-PHOENIX, we have compared plasma deposition and sputtering timescales to those from neutral gas-phase surface chemistry to ascertain their regimes of influence. We calculated the plasma sputtering yield and discuss the circumstances where plasma sputtering dominates over deposition.

Within the highest dust density cloud regions, plasma deposition and sputtering dominates over neutral gas-phase surface chemistry if the degree of ionisation is greater than or similar to 10(-4). Loosely bound grains with surface binding energies of the order of 0.1-1 eV are susceptible to destruction through plasma sputtering for feasible degrees of ionisation and electron temperatures; whereas, strong crystalline grains with binding energies of the order 10 eV are resistant to sputtering.

Conclusions: The mathematical framework outlined sets the foundation for the inclusion of plasma deposition and plasma sputtering in global dust cloud formation models of sub-stellar atmospheres

Pinning down the collisionless microtearing mode

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Microtearing modes are fine-scale instabilities with large toroidal and poloidal mode numbers that can exist in tokamak plasmas. They can be driven in the vicinity of rational flux surfaces by electron temperature gradient [1,2] and can increase electron thermal transport [1,4]. The stability of microtearing modes has previously been shown to

be influenced by trapped electron dissipation, ion magnetisation and collisional broadening of passing electron Landau resonance [3] and in some cases can be extremely unstable [4].

The classic model for microtearing modes in a sheared slab magnetic geometry shows that they are stable at either high or low collision frequencies, and destabilised by the electron temperature gradient at intermediate collision frequency [1,2]. However, recent research has found that the modes can be unstable even at low collision frequency at toroidal geometry [4,5]. We have explored an evolution from toroidal to slab geometry using the gyrokinetic code GS2 [6,7] and found that microtearing modes in collisionless plasmas are actually also unstable even in slab geometry with this more complete plasma description. We have carefully re-derived the instability eigenmode equations in slab geometry and checked the assumptions for the classic tearing mode as well as different dominating physics in different geometries. This starts to shed some light on the possible mechanism for driving the collisionless microtearing instability in slab geometry.

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Debye-Waller for Temperature Measurement of Shock Compressed Solids

A Poole[1], A Comley[2], E Floyd[2], J Foster[2], C Lumsdon[1], D McGonegle[3], A Meadowcroft[2], S Rothman[2], J Wark[3], and A Higginbotham[1]

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The study of laser-shocked solids is of increasing importance. Numerous fields of research draw from these experiments, including: planetary physics, inertial confinement fusion, and the search for novel materials. The timescale of these experiments is typically of the order of nanoseconds, requiring the implementation of finely timed measurement solutions; however, the accurate measurement of material temperature has been a longstanding problem in the field. Temperature can be inferred from spectrometric data; the radiation emitted from the material is attributed to a corresponding temperature based on the distribution of wavelengths. Unfortunately, many materials of interest are opaque, and thus the emitted radiation is reabsorbed in the bulk. Alternative temperature measurement techniques have been attempted, though the error in measured temperature often exceeds tens of percent.

To address this issue, a temperature measurement scheme has been devised involving x-ray diffraction. The intensity of diffracted x-rays depends on temperature via the Debye-Waller effect; as the temperature of a material increases, the observed diffraction decreases in intensity. An experiment was undertaken at the Orion Laser Facility to prototype this scheme. The experimental geometry will be presented along with a discussion of the results and implications for the future of the technique.

Particle-in-cell simulations of filamentation in laser wakefields

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The laser filamentation instability is observed in plasma wakefields at sub-critical densities, and in high density inertial fusion plasmas. This leads to non-uniform particle acceleration in the wakefield or non-uniform target compression respectively. Here, we present simulation results on laser filamentation in plasma wakefields. Two-dimensional simulations have been carried out using the particle-in-cell code Osiris. The filament intensity was found to increase exponen-tially before saturating. The maximum amplitude to which the highest intensity filament grew for a specific set of parameters was also recorded, and plotted against a corresponding param-eter value (plasma density, laser amplitude, laser pulse duration and interaction length). Clear, positively correlated linear trends were established between plasma density, transverse wave number, laser pulse amplitude and maximum filament amplitude. Plasma density and maximum filament amplitude also showed a positive correlation, which saturated above a certain plasma density. Pulse duration and interaction length did not affect either filament intensity or the trans-verse wave number of the filamentation in a predictable manner. There was no discernible trend between pulse amplitude and filament width.

Producing shock-ignition like pressure profiles by indirect drive

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The shock ignition scheme is an alternative Inertial Confinement Fusion ignition scheme that offers higher gains and a robustness to hydrodynamic instabilities. Conventional approaches to shock ignition have only considered the use of a direct drive laser source. However, an indirect-drive approach would allow for experiments to be carried out in the near future, without the need to modify existing ignition scale facilities to a direct drive set-up. One and two-dimensional radiation hydrodynamic simulations have been performed using the codes HYADES and h2d. The simulations investigated the laser power profiles that would be required to produce shock ignition pressures using indirect drive x-rays. It was found that 230Mbar pressures could be achieved with a peak power of 400TW. In addition, the rate of pressure increase in the final pressure spike is similar to the expected requirements for directly driven shock ignition.

This work was supported by the Engineering and Physical Sciences Research Council [EP/L01663X/1].

Generation of non-thermal plasmas over large and complex surfaces

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University of Southampton, UK

Non-thermal plasma, also known as cold plasma, is a plasma operating at room temperature and pressure. The unique physical and chemical characteristics of non-thermal plasma, including the presence of reactive species and high electron density, bring a broad spectrum of potential plasma applications in biomedical treatment, environment remediation, surface modification and electric countermeasure. Although electromagnetic wave manipulation and bacteria inactivation capabilities of non-thermal plasma are well demonstrated, one of remaining technical challenges is generating uniform plasma over complex and/or large surface such as human bodies and vehicles. The conventional non-thermal plasma sources are only providing plasmas over flat, rigid and pre-defined surfaces. In this study, we will propose a new flexible and scalable plasma source with implementing printed electronics and knitting technique.

Figure 1 a) shows a non-thermal plasma source printed on thin polyamide film using a Dimatix DMP-2850. The use of printed electronics techniques provides a high scalability, with the ability to fabricate plasma sources in various sizes and substrates. In this study, we also implement a modular approach to enhance the scalability of a plasma source by assembling multiple plasma sources. The flexibility of a plasma source is promoted using a flexible polyamide substrate. The modular plasma sources printed on a flexible substrate will bring the capability to generate non-thermal plasmas over complex geometries. This study considers additional fabrication method for the comparison, which is using knitting techniques. Figure 1 b) shows a flexible plasma source fabricated using knitting technique, known as a plasma yarn. The plasma yarn consists of a cylindrical high voltage electrode and an outer grounded knitted mesh electrode. The high-voltage electrode is enclosed using a silicon thus enhancing the electrical safety. As a plasma yarn has enhanced flexibility, we can use them to knit a larger plasma fabric/blanket including complex geometries.

The flexibilities of plasma sources fabricated using both printing and knitting techniques will be quantified using a scanning electron microscope (SEM) which will monitor structural failure for varying bend radii. The plasmas generated by each source will be monitored and characterised using electrical and optical diagnostics including Optical Emission Spectroscopy (OES). Therefore, we will investigate the correlation of the power consumption and the plasma characteristics of the respective fabrication techniques. Flexible plasma sources fabricated using different methods will be assessed in terms of the uniformity of a plasma and the flexibility and scalability of the system.

Fig. 1: (a) Printed non-thermal plasma source on polyamide film

Fig. 1: (b) Plasma yarn with a knitted mesh electrode

(Invited) Reduced and Machine Learning Models in Fusion Plasma Simulations

S Smith[1], O Meneghini[1], M Fasciana[2], A Tema Biwole[2], G Staebler[1], E Belli[1], B Lyons[1], J McCleneghan[1], B Grierson[3] and G Snoep[4]

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We have devised a series of machine learning (ML) models, which greatly speed up the calculation of pedestal structure models and turbulent and neoclassical models of transport in magnetically confined plasmas. These models are now implemented in transport solvers embedded within larger workflows such as device design. The increased speed allows for more efficient and thorough investigation of design parameter space, and could be used in the future for real time plasma control purposes. These ML models are trained on a variety of input parameters likely to be encountered during typical modeling of existing and future tokamaks. The increased speed enables the efficient iteration between typical electron and main ion transport simulations, the evolution of the impurity density,

and a realistic pedestal. The integration is achieved within the OMFIT integrated modeling framework [1] in its STEP module.

In Fig. 1 is shown a validation of the integrated and iteratively converged workflow for a DIII-D discharge. The experimentally measured profiles are given by the dashed black lines, with gray uncertainty bands. The other profiles are predicted, with the only constraints being the electron density and ion rotation at the pedestal top and the integrated carbon content. The green case has the same total carbon content as the experiment, while the red case has 1.5 times more carbon than experiment, and yellow has 0.5 times less than experiment. Application of the workflow to predict ITER stationary profiles indicates that increasing the Neon density increases the edge pedestal temperatures (the pedestal prediction is sensitive to Z_{eff}). However, the increased pedestal temperature does not result in higher fusion yields because the core D-T fuel densities decrease as the Neon density increases.

While ML methods can be thrown blindly at a dataset, we have found that physics motivated approaches, such as using diffusivities instead of fluxes during training, or exploiting the linear nature of neoclassical transport, can greatly improve the ability for ML models to reproduce their physics based counterparts.

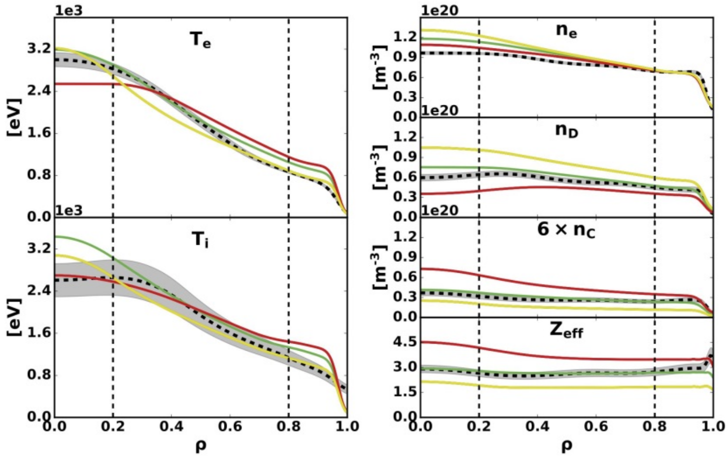

Fig. 1: Experimentally measured (black with gray band) and predicted (yellow, green, red) profiles of electron and ion temperatures and densities. The green case has the same total carbon content as the experiment, while the red (yellow) case has 1.5 (0.5) times more (less) carbon than experiment.

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Velocity-space redistribution of fast ions during sawtooth crashes in the MAST spherical tokamak observed using fast ion deuterium-alpha spectroscopy

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Energetic neutral beam injection (NBI) was commonly used during plasma pulses in the Mega Amp Spherical Tokamak (MAST). Deuterium (D) ions from ionisation of NBI neutrals provided most of the heating in these pulses, therefore high plasma performance required the ions to be adequately confined. Ideally, beam-injected ions in tokamak plasmas should be confined “classically”, slowing-down and undergoing radial transport solely through Coulomb collisions. However non-classical redistribution of fast ions in both position and velocity space often occurs for several reasons, including “sawtooth” crashes, which are observed as a collapse in the plasma core

electron temperature and are triggered by a kink-unstable twist in the magnetic field. The response of the fast ions to such instabilities can be studied by detecting Balmer-alpha light emitted when some of the ions capture an electron into an $n = 3$ excited state from a beam neutral. This technique, known as fast ion Da (FIDA) spectroscopy, is made possible by the fact that the high line-of-sight velocities of the beam ions Doppler shift the light by several nanometres from the Da rest wavelength of 656.1nm. Following initial studies by Cecconello *et. al.* [1,2] on the effect of the sawtooth instability on the fast-ion population of a MAST plasma based on neutron and FIDA data, we have performed more detailed analysis of FIDA data utilising the FIDASIM code [3]. In [2], three models of the crash (generally referred to as "standard Kadomtsev", "Kadomtsev ergodic mixing" and "Porcelli": see [2] and references therein) were used in simulations performed using the TRANSP/NUBEAM code [4], and it was found that neutron camera data could not be used to distinguish between the models. Synthetic FIDA spectra before and after a sawtooth crash, generated with FIDASIM using the three models, are almost identical, and, before the crash, have a similar slope to the measured spectrum (Fig. 1). However, the measured spectrum after the crash is flatter than the pre-crash spectrum (Fig. 1). In the measured spectra FIDA data have been aggregated over several time points. Since the Doppler shift of the Da light is proportional to the fast ion line-of-sight velocity, the flattening of the spectrum in Fig. 1 suggests that the sawtooth-induced fast ion redistribution is greater at low energies than high energies, or that the sawtooth is causing energy-dependent pitch angle scattering, or that the electric field associated with the sawtooth is accelerating beam ions to higher energies. These interpretations of the FIDA data will be discussed and evaluated.

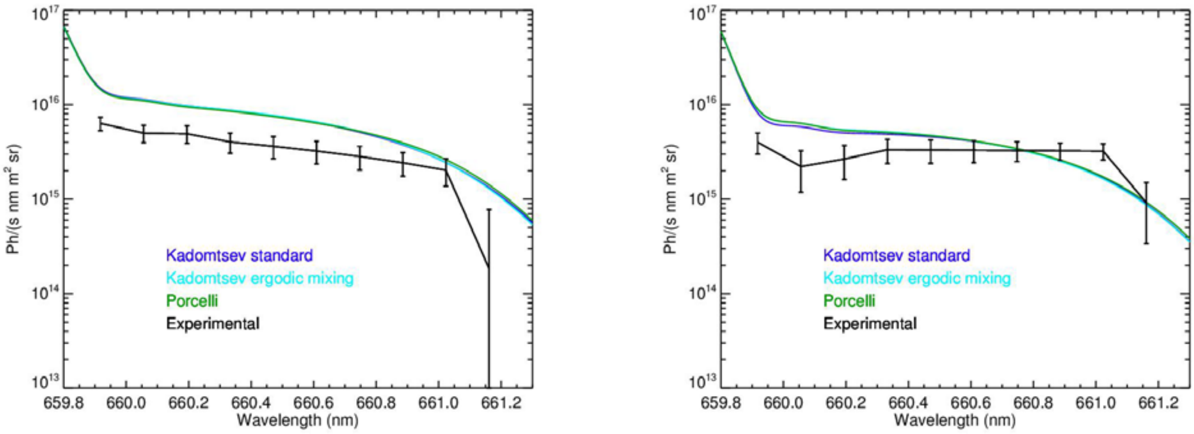

Fig. 1: Comparison of synthetic (coloured curves) and experimental (black curves and data points) FIDA spectra, before (left) and after (right) a sawtooth crash.

[1] M. Cecconello et al., Plasma Phys. Control. Fusion 57, 014006 (2015)
[2] M. Cecconello et al., Plasma Phys. Control. Fusion, 60, 055008 (2018)
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[4] A. Pankin et al. Comput. Phys. Commun. 159, 157 (2004)

(Invited) Towards thermonuclear plasmas: preparations for deuterium-tritium operation with an ITER-like wall in JET

F Rimini[1, 2] and the JET Contributors[3]

[1]CCFE, UK, [2]UKAEA, UK, [3]EUROfusion Consortium

With its ITER-like beryllium main chamber wall and tungsten divertor combined with DT fusion capability, JET has a unique role to play in the preparations for ITER experiments. The JET scientific programme in 2019/2020 has been,

therefore, organized in a set of campaigns with various hydrogenic isotopes, leading to an extensive phase dedicated to DT plasmas.

Specific high level objectives have been agreed for this programme, aiming to deliver high fusion performance, new insights into alpha-particle effects and ITER-relevant core and edge physics results. The lessons learnt in the previous DT experiment on JET in 1997 are integrated in the plan for the experiments; for example, isotope effects will be addressed more widely by looking extensively at low fusion yield TT plasmas to *bracket* DT physics effects. The plan will, also, include dedicated tests of high priority items for ITER, e.g. studies of runaway electron control and suppression.

Two complementary integrated scenarios are being developed to aim at high sustained DT fusion performance with fusion power P_{fus}=15 MW for 5 seconds. They both rely on H-mode confinement at high input power but differ in the plasma parameter space they explore. The baseline scenario (normalised beta $\beta_N \sim 1.8$ and normalised confinement factor $H_{98} \sim 1.0$) concentrates mainly on achieving high confinement and fusion reactivity by pushing the operation towards high plasma current. On the other hand, the hybrid scenario ($\beta_N \sim 2$-3 and $H_{98} > 1.0$) exploits the advantages of operating at higher normalised beta with a shaped current profile such that the safety factor q (the number of toroidal circuits made by a magnetic field line in one poloidal circuit) in the plasma core is above or close to unity. Encouraging results, very similar in the two scenarios in terms of extrapolated DT fusion power, were achieved in previous JET DD campaigns.

A different plasma scenario has been developed with elevated q-profile, q_{min}~2, for fusion alpha-particle studies, relying on short, 1-2 seconds, *burst* of high fusion performance. Extrapolation from the results obtained so far in DD confirm the potential to observe alpha-particle effects, such as induced TAE activity in the after-burn phase after the additional heating is switched off.

The isotope physics studies will, generally, use tailored versions of the H-mode scenarios developed as part of the fusion performance to investigate the isotope dependence of H-mode physics, with a metal Be/W first wall, going from pure hydrogen to pure tritium and, eventually, to the 50/50 DT mixture. These activities will cover not only experimental analysis and modelling of the expected core and pedestal effects, already observed in other tokamaks and in a previous DT campaign on JET, but will also aim at demonstrating integrated wall-SOL-pedestal solutions and validate predictive edge and divertor physics models for ITER.

In this talk we will start from the results obtained so far in DD plasmas to describe their extrapolation to DT conditions, highlight the operational challenges facing their optimization to achieve the JET DT aims and touch on the physics issues still open and needing further theoretical and numerical modelling effort.

Poster Session

P1. Thermal Conduction in Odin

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Odin is an Arbitrary Eulerian-Lagrangian (ALE) two dimensional code based at Warwick University but written as a collaboration among several UK universities, STFC and AWE. It uses radiation magnetohydrodynamic (MHD) to simulate high energy density (HED) environments. Odin has both implicit and explicit thermal conduction routines which function independantly. The explicit routine is a Pert 1981 diffusion model implemented by a Meyer et al 2012 Super-Stepping routine, the implicit is a Sheng et al 2008 method which uses PETSc to implement a BiCGSTAB matrix inversion. The code provides a useful platform to benchmark and compare the two systems in not just simple tests, but full scale inertial confinement implosions and other HED environments. In addition, it is important to consider how difficult each routine was to create, ease of use and how complex it is to upgrade with a

P2. Novel coatings for transmission electron microscopy sample preparation

E Hookham[1], O Rybdylova[2], S Busbridge[2], R Holmes[1], D Perry[1], and D Sarker[2]

[1]Quorum Technologies, UK, [2]University of Brighton, UK

Sample preparation of TEM grids can require adaptation of the surface polarity to allow for easy spread of aqueous solutions. This can be done using plasma enhanced chemical vapour deposition (PECVD), but little research has been carried out on modelling the movement of the vapour through a vacuum chamber. This a challenging concept, but one which could be utilised in improving process efficiency and coating quality. Methanol is known to produce a hydrophobic coating when deposited using a glow discharge, but how methanol moves through a vacuum has not previously been modelled.

A model of the processes using the Computational Fluid Dynamics software ANSYS CFD has been developed. A 2D compressible flow of chamber species defined by the methanol chemical reactions follows the methodology proposed in [1]. The flow domain is shown in fig. 1 where the distribution of electron density is taken as in [2].

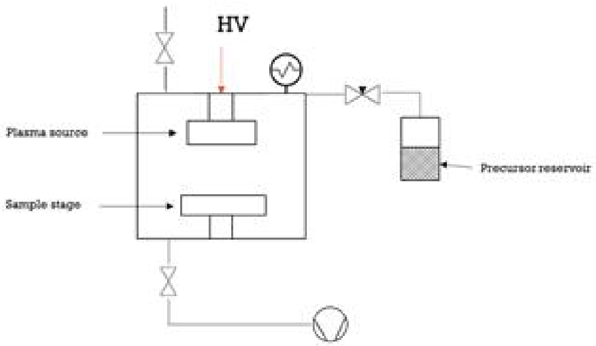

Fig. 1: Flow domain diagram of plasma chamber.

[1] Crose, M.; Tran, A.; Christofides, P.D. Multiscale Computational Fluid Dynamics: Methodology and Application to PECVD of Thin Film Solar Cells, *Coatings*, **7**, 22, (2017).

[2] Park, S.; Economou, D. A mathematical model for etching of silicon using CF4 in a radial flow plasma reactor, *J. Electrochem. Soc,* **138**, 1499–1508, (1991).

P3. Compact, lightweight, high power mm-wave sources using a pseudospark sourced electron beam

A Cross[1], J Xie[1], H Yin[1], L Zhang[1], K Ronald[1], A Phelps[1], W He[2], G Shu[2], J Zhao[3], X Chen[4], Y Alfadhl[4], and J Zhang[4]

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The pseudospark (PS) discharge is a form of low-pressure gas discharge, capable of supporting extremely high currents with 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 propagate through sub-millimetre planar structures via ion channel focusing[3]. Simulations have shown that the pseudospark plasma sourced electron beam will propagate within a 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 32kV, 5A pseudospark-sourced sheet electron beam (PS-SEB) has been used to drive a planar slow wave extended interaction oscillator (EIO) structure. The PS-SEB based EIO produced ~1.2 kW peak output power at 105GHz, an increase of six times in the measured power from a W-band EIO based on a pseudospark-sourced pencil electron beam[6]. Such a methodology offers a promising solution for portable, low-cost and powerful millimetre-wave and terahertz-wave radiation sources[7]. Progress in the design and simulation of a 352 GHz EIO based on a PS-SEB will be presented.

[1] J. Christiansen and C. Schultheiss, "Production of high-current particle beams by low-pressure spark discharges", Z. Physik A, 290, pp. 35-41, 1979.
[2] H. Yin, et al., "Single-gap pseudospark discharge experiments," J. Appl. Phys., 90, pp. 3212-3218, 2001.
[3] D. Bowes, et al., "Visualization of a Pseudospark-Sourced Electron Beam", IEEE Trans. Plasma Science, 42, (10), pp. 2826-2827, 2014.
[4] J. Zhao, et al., "Influence of the electrode gap separation on the pseudospark-sourced electron beam generation," Phys. Plasmas, 23, 073116, 2016.
[5] W. He, et al., "Generation of broadband terahertz radiation using a backward wave oscillator and pseudospark-sourced electron beam," Appl. Phys. Lett., 107, 133501, 2015.
[6] G.X. Shu, et al, "Study of a sub-THz Extended Interaction Oscillator Driven by a Pseudospark-Sourced Sheet Electron Beam", IEEE Trans. on Elect. Dev., 63, pp. 4955-4960, 2016.
[7] J. Zhao, et al, "Experiments on W-band extended interaction oscillator with pseudospark sourced post-accelerated electron beam," Phys. Plasmas, vol. 24, no. 7, pp. 060703-1-4, 2017.

P4. Absolute atomic chlorine density measurements in the effluent of a radio-frequency atmospheric pressure plasma

J Boothroyd[1], A Gibson[2], M Shaw[1], S Schröter[1], T Gans[1], and T Dillon[1]

[1]University of York, UK, [2]Ruhr University Bochum, Germany

A radio-frequency atmospheric pressure capacitively coupled argon/chlorine plasma source, similar in design to the 'COST reference microplasma jet' [1], is used to generate atomic chlorine. The absolute density of atomic chlorine in the effluent of the plasma source is investigated using a volatile organic compound marker and proton transfer reaction mass spectrometry (PTR-MS). The marker compound is introduced into the plasma effluent stream radially in a flow tube, titrating the atomic chlorine present. The remaining marker compound from the flow tube is then measured using PTR-MS.

Highly reactive atomic chlorine can be crucial in the kinetics of atmospheric chemistry and low pressure plasma processing. Due to its very short lifetime and associated strong spatial gradients of concentrations, it is very difficult

to make direct measurement of its reactivity and concentration in the atmosphere. Nevertheless, using an atmospheric pressure plasma instead of mercury vapour lamp to produce atomic chlorine for use in the 'Comparative reactivity method' [2] an indirect measurement of the reactivity (or loss rate, in s^{-1}) of atomic chlorine in a sample of ambient air can be investigated.

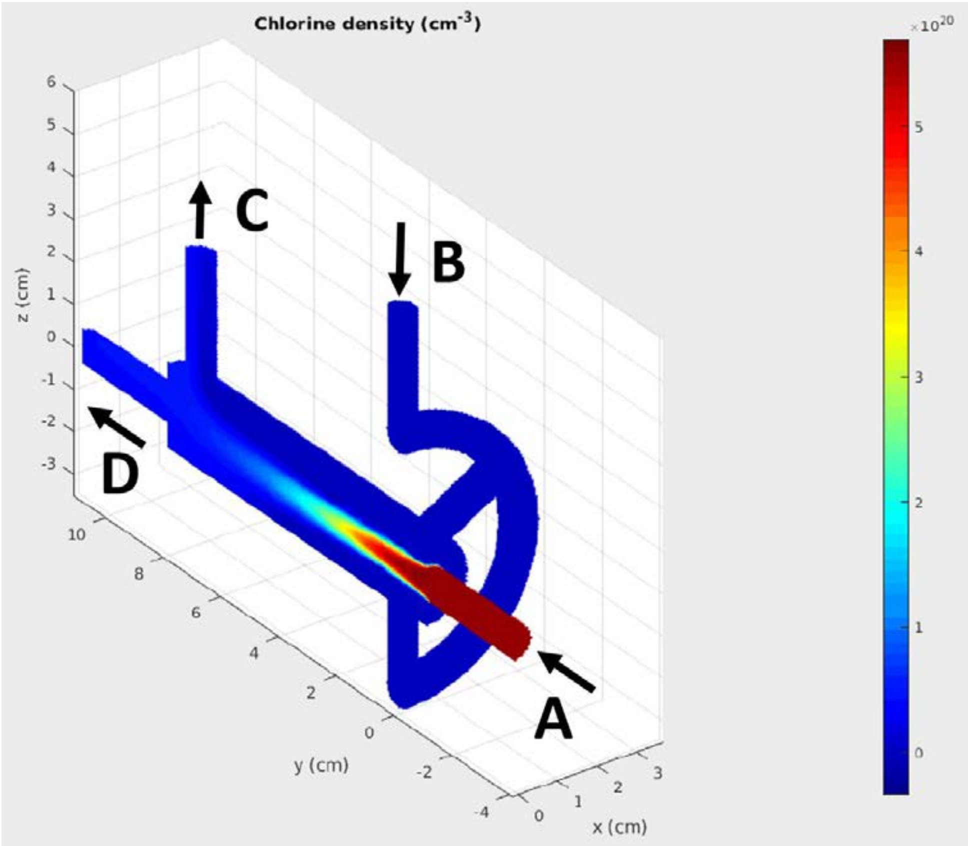

Fig. 1: Cross section of COMSOL simulation of the reactor vessel showing mixing and titration of the plasma generated atomic chlorine (arm A) by the marker compound (arm B). The PTR-MS is attached to arm D, excess flow out through arm C. Credit to S Schröter for the simulation.

[1] J Golda, J Held, B Redeker, M Konkowski, P Beijer, A Sobota, G Kroesen, N St J Braithwaite, S Reuter, M M Turner, T Gans, D O'Connell, V Schulz-von der Gathen, J. Phys. D 49, 084003 (2016).

[2] V Sinha, J Williams, J N Crowley, J Lelieveld, Atmos. Chem. Phys. 8, 2213-2227 (2008).

P5. RF compensation in low temperature plasmas

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Radio frequency (RF) fields in plasmas distort the current-voltage (I-V) characteristic of a Langmuir probe. This widens of the transition region and overestimates the electron density and temperature. It is shown that the first derivative of an I-V curve contains amplitudes of the residual RF sheath voltage. This provides a measure of compensation. By passively compensating the probe RF amplitudes of 29.5 V to 3.2 V have been obtained. Preliminary compensation experiments have reduced the measured Te from 15.9 eV to 2.4 eV. Furthermore, it is

shown that the probe area affects the sheath voltage and impedance. It is found that an increasing probe area results in a decrease in electron temperature from 15.9 to 7.6 eV.

The effect of plasma potential oscillations on a Langmuir probe I-V curve is well-documented [1]. An RF voltage drop across the sheath distorts the time-averaged I-V curve because of it's nonlinearity. Passive [2] and active [3] compensation methods have been developed to remove RF effects. Passive compensation is simpler to implement than active and does not require complex circuitry. The aim of passive compensation is to increase probe circuit input impedance to RF relative to the sheath impedance [2]. This is usually achieved using a compensation electrode and an inductance chain in the probe stem. This work aims to develop effective passive probe compensation for accurate plasma parameter measurements.

Experiments were performed in a capacitively coupled argon discharge with a pressure of 3 - 6 Pa and RF power 10 - 20 W at 13.56 MHz. Measurements were taken with 1 cm long tungsten Langmuir probe tips of 12.5, 25 and 50 μm radii with an external low-pass filter (cut-off frequency of 1 MHz). Inductors were placed in a ceramic stem near the probe tip without a compensation electrode. The first derivatives of the I-V curves with different inductors are shown in fig. 1. The distortion of the I-V curve results in additional peaks in the first derivative [4]. The voltage difference between these peaks and the plasma potential is the RF voltage across the sheath. The 22 and 100 μH inductors resulted in a lower input impedance to RF than no inductor. Preliminary compensation experiments with a 470 μH inductor gave an electron temperature of 2.4 eV with 3.2 V across the sheath.

In a separate experiment, without inductors, I-V curves were taken with different probe radii. Electron temperatures of 15.9 eV (12.5 μm radius), 8.5 eV (25 μm radius) and 7.6 eV (50 μm radius) were obtained. This shows that electron temperature and RF voltage are larger for a smaller probe.

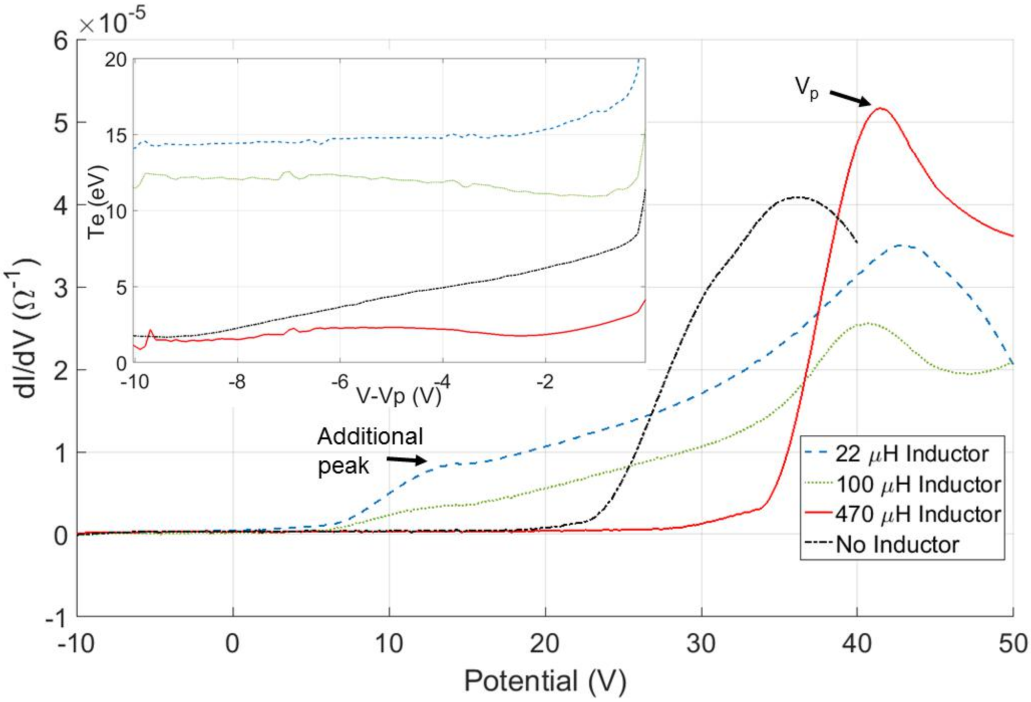

Fig. 1: First derivatives of I-V curve with an inductor in 6 Pa, 10 W plasma. Inset: Te 10 V below V_p.

[1] A Boschi and F Magistrelli. Il Nuovo Cimento, 29(2),1963.
[2] B M Annaratone and N S J Braithwaite. Measurement Science and Technology, 2(8):795, 1991.
[3] A Dyson et al. Measurement Science and Technology, 11(5), 2000.
[4] M Hannemann and F Sigeneger. Czechoslovak Journal of Physics, 56(2), 2006.

P6. Observations and modelling of ion cyclotron emission observed in JET plasmas during ion cyclotron resonance heating

K McClements[1], A Brisset[2], B Chapman[3], S Chapman[3], R Dendy[1], P Jacquet[1], V Kiptily[1], M Mantsinen[4], and B Reman[3]

[1]CCFE, UK, [2]Université Paris-Sud, France, [3]University of Warwick, UK, [4]Barcelona Supercomputing Center, Spain

Measurements are reported of electromagnetic emission close to the cyclotron frequency of energetic ions in JET plasmas heated by waves in the ion cylotron range of frequencies (ICRF) [1]. Hydrogen was the majority ion species in all these plasmas. The measurements were obtained using a sub-harmonic arc detection system in the transmission lines of one of the ICRF antennas. The measured ion cyclotron emission (ICE) spectra were strongly filtered by the antenna system, and typically contained sub-structure, consisting of sets of peaks with a separation of a few kHz, suggesting the excitation of compressional Alfvén eigenmodes closely spaced in frequency. In most cases the energetic ions can be clearly identified as ICRF wave-accelerated ^3He minority ions, although in two pulses the emission may have been produced by energetic ^4He ions, originating from third harmonic ICRF wave acceleration. It is proposed that the emission close to the ^3He cyclotron frequency was produced by energetic ions of this species undergoing drift orbit excursions to the outer midplane plasma edge. Particle-in-cell and hybrid (kinetic ion, fluid electron) simulations using plasma parameters corresponding to edge plasma conditions in these JET pulses, and energetic particle parameters inferred from the cyclotron resonance location, indicate strong excitation of waves at multiple ^3He cyclotron harmonics, including the fundamental, which is identified with the observed emission. These results underline the potential importance of ICE measurements as a method of studying confined fast particles that are strongly suprathermal but have insufficient energies or are not present in sufficient numbers to excite detectable levels of gamma-ray emission or other collective instabilities.

[1] K. G. McClements *et al.*, Nucl. Fusion 58, 096020 (2018).

P7. Full orbit calculations of resonance maps for fast particle-driven Alfvénic modes in the MAST spherical tokamak

T Sun[1], J Buchanan[2], M Fitzgerald[2], and R Sharples[1]

[1]Durham University, UK, [1]CCFE, UK

Fast ions can be generated in tokamaks by several heating mechanisms including neutral beam injection (NBI) and radio frequency wave heating. Thesee intense populations of energetic particles can drive Alfvén eigenmodes unstable and produce electromagnetic perturbations. These perturbations can redistribute the driving particles leading to enhanced energy, density and momentum transport towards the device wall. In order to study the control of such Alfvénic instabilities, two NBI beams were applied on the Mega-Amp Spherical Tokamak (MAST) with the first beam destabilising Alfvén eigenmodes and the second one intended to suppress the instabilities. Magnetic perturbation measurements clearly showed the excitation of Alfvén instabilities in the presence of beam injection. The growth of instabilities takes place when there is a strong wave-particle resonance producing a large absorption of energy. Based on the collisionless drift-kinetic model, a derived wave-particle resonance condition has shown that periodic motions both in the toroidal and poloidal directions can drive Alfvénic instabilities and contribute to the growth rate. In this simulation work, particles were launched with a full range of energies in MAST for a given beam injection angle $\lambda = v_{||}/v$. By tracking the full orbits of the markers in an equilibrium magnetic field, poloidal bounce and toroidal precession frequencies and associated resonant regions in phase space can be found. The simulation has shown that the particles at $\lambda = 0.76$ will not be confined in MAST when the energy is above 30 keV. The optimal injection positions and energies of NBI beams can also be inferred through the resonant map.

P8. High bandwidth FPGA based diagnostics for MAST-U

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[1]Durham University, UK, [2]UKAEA, UK, [3]University of York, UK

As simulations become increasingly precise it becomes necessary to constrain and verify results with increasingly precise data. This calls for high bandwidth, cost effective, data acquisition systems. Field Programmable Gate Array (FPGA) technology is a form of hardware programmable computer useful for high bandwidth I/O applications. This makes them ideal for research applications where flexibility is highly valued.

I will present two systems built for use on the Mega Amp Spherical Tokamak Upgrade (MAST-U) located at Culham Centre for Fusion Energy (CCFE) in Oxfordshire, UK. The first is a fission chamber acquisition system for neutron detection which provides single pulse counting, DC current measurement and Campbell mode simultaneously at a rate of 1 MHz. The system applies a real-time finite impulse response (FIR) filter to improve neutron pulse detection and increase the Signal-to-Noise Ratio (SNR) . Calibration work at the National Physical Laboratory (NPL) has been used to calibrate and benchmark the system.

The second is the Synthetic Aperture Microwave Imager 2 (SAMI-2). This diagnostic will measure the edge current density on MAST-U using two-frequency 2-D doppler backscattering. Data will be collected from 32 antennas, using a novel planar and sinuous design, at 2 polarisations, and then packaged and sent using 10 Gigabit ethernet to Intel network cards installed in an acquisition PC. Both systems use Consumer-Off-The-Shelf (COTS) components to provide high data rate custom instrumentation.

This work is supported by the Engineering and Physical Sciences Research Council [EP/L01663X/1 and EP/s018867/1], and by the RCUK Energy Programme [Grant Number EP/P012450/1].

P9. Assessing the power loss through infrared thermography in MAST

M Dunn[1], K Gibson[1], and A Thornton[2]

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For fusion power to be a commercial success in the future, one of the major issues that must be addressed is identifying a means of controlling the power arriving at the plasma facing components. One method for achieving this is to use alternative power exhaust (divertor) configurations, such as the Super-X divertor proposed for MAST-U [1]. In the Super-X, the power is spread over a larger area, and the radiated fraction is increased by cold gas puffing to induce detachment, where very little power and very few particles are deposited at the targets.

Understanding power flows in existing tokamaks is important to see how alternative configurations compare. It is necessary to assess both the flow of power from the core to scrape off layer (SOL) and subsequently along the SOL to the divertor target plates. Such an analysis needs to take account of energy deposited in the core (through ohmic and auxiliary heating), as well as radiation, and heat and particle transport processes in the core and SOL/divertor regions. This requires the integration of a variety of diagnostic measurements, for example target power loads from infrared thermography, bolometry and accurate equilibrium reconstructions. Power balance studies also allow the measurement of asymmetry of power deposition between divertor targets.

In this work we report on analysis of a database of MAST pulses covering a range of divertor configurations, including double null and lower single null. Results show that for a true even split in power between the upper and lower divertors, there is an apparent need to operate the plasma with a small asymmetry in magnetic geometry, due to grad-B drift, consistent with previous work [2]. In such balanced double null discharges, we also identify a strong in/out asymmetry in power exhaust, with up to 90% of the power arriving at the outer divertor plates.

We will report on ongoing studies to further refine the power balance calculations that consider a correction to the auxiliary heating deposition, and properly take account of the 3D tile geometry in the divertor region. We will finally discuss the implementation of these analysis techniques to experiments on MAST-U, especially in studies of advanced divertor configurations such as Super-X.

[1] W Morris, JR Harrison, A Kirk et al, *IEEE trans. Plasma Science,* 45 5 (2018)

[2] De Temmerman et al, *Plasma Phys. Control Fusion* 52 (2010) 095005

P10. Progress on a helicon plasma apparatus for multifrequency microwave-plasma interactions

K Ronald[1], K Wilson[1], A Phelps[1], A Cairns[2], B Bingham[3], B Eliasson[1], M Koeple[4], A Cross[1], D Speirs[1], C Robertson[1], P MacInnes[1], and C Whyte[1]

[1]University of Strathclyde, UK, [2]University of St Andrews, UK, [3]STFC Rutherford Appleton Laboratory, UK, [4]West Virginia University, USA

Energy may be transferred between one or more EM waves and plasma waves through parametric interactions in plasma. Where the plasma is below one-quarter critical density, two injected EM waves can excite an rapidly growing electrostatic Langmuir oscillation, (Raman interaction), whereas plasma above one-quarter critical density can also couple two EM modes mediated by an ion-acoustic wave (Brillouin scattering). These types of interaction mediated by Langmuir and ion acoustic waves are important in ionospheric radio-physics experiments and for a range of laser plasma interactions. Microwave signals with normalised intensities approaching those used in some recent laser plasma interactions can be generated using powerful and highly flexible microwave amplifiers. The very accurate control of wave frequency, amplitude and phase possible with such powerful microwave generators, combined with the options of insertion plasma diagnostics in the relatively tenuous plasma will enable precision experiments to understand the nonlinear electrodynamics of these processes.

Multi-wave interactions can potentially address challenges in heating and current drive in future magnetic confinement fusion (MCF) reactors where increased spacing between the plasma and antenna may make direct heating of the ions harder. In the case of current spherical aspect ratio tokamaks, the relatively high density compared to the magnetic field inhibits access at the low harmonics of the electron cyclotron frequency, desirable for EC heating and current drive. 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 large diameter coils. The plasma will be created by an RF helicon source, using a flat spiral antenna near the end of the magnetic field system to generate a dense, large, cool plasma with high ionisation fraction (an electron number density up to $10^{18}m^{-3}$ is expected with several kW of drive power). Helicon sources have attracted interest as a method of generating plasma for industrial processing applications, and for potential applications in thrusters, besides their use in fundamental physics research. A range of frequency-flexible microwave sources, initially TWT amplifiers and magnetron oscillators, will provide beams to enable multi-wave coupling experiments. The paper will present the development of the apparatus and the research programme.

The authors gratefully acknowledge support from the EPSRC, MBDA UK Ltd and TMD Technologies Ltd.

P11. The importance of surface tension gradients in plasma-liquid treatments

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Loughborough University, UK

Recent advancements in plasma-liquid interactions range from chemical disinfection, medicine and agriculture to nano-material fabrication and analytical chemistry. While there is a rapid growth in plasma-liquid applications, guidelines for system design and reactor optimization are limited. To study the main mechanisms affecting the mass transfer between an atmospheric pressure plasma jet (APPJ) and a liquid medium, a batch reactor was designed and investigated. Computational and experimental results show that while the external gas flow and the natural convection imposed by temperature gradients play a more significant role in the liquid mixing patterns than electrically driven forces, surface tension gradients can completely reverse flow patterns and enhance the local liquid velocity (figure 1). These gradients can be generated by chemical reactions at the liquid interface exposed to the plasma and they can significantly affect the mixing efficiency in the liquid, thereby reducing the required treatment time for a given application.

For the particular batch reactor used in this study, the treatment time could be reduced from hours to less than 10 minutes by exploiting the flows induced by surface tension gradients. It is also shown that when solutions of silver and gold salts are exposed to the plasma, inducing surface tension gradients leads to an increase in the rate of nanoparticles formation.

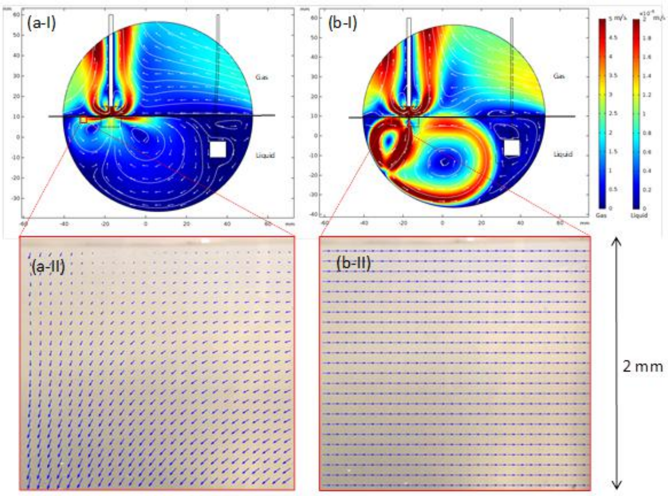

Fig. 1: Simulated local velocity field during plasma treatment for de-ionized water-salt (a-I) and for de-ionized water-salt and 1% mass PVA (b-I). The local velocity direction is reversed, and the magnitude is increased as confirmed by PIV analysis plotted in (a-II) and (b-II).

P12. Generation and amplification of laser modes with higher order polarisation via Raman amplification

R Trines[1], J Vieira[2], R Fonseca[2], T Mendonça[2], L Silva[2], and B Bingham[1]

[1]STFC Rutherford Appleton Laboratory, UK, [2]Instituto Superior Tecnico, Portugal

In conventional optics, pulses with higher-order types of polarisation can only be produced at relatively low powers. Here we show how pulses with higher-order Poincaré polarisation, which includes radial or azimuthal polarisation, can be amplified to ultrahigh powers via Raman amplification in plasma.We present a new scheme where we use two pump beams with orthogonal modes of simple linear or circular polarisation. This way, we do not require a high-

energy pump beam with some form of higher order polarisation, which may be difficult to produce. Applications of high-power pulses with azimuthal polarisation include generation of a small but intense θ-pinch for localised plasma compression and heating, with applications in laser-driven nuclear fusion.

P13. Cusp soliton in piezoelectric semiconductor plasmas

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Government College University, Pakistan

The plasma effects, nonlinearities and electro-mechanical coupling effects have been investigated extensively due to its various industrial and technological applications. The piezoelectric coupling of Langmuir waves with lattice ion vibrations in linear as well as nonlinear regime via nonlinear ponderomotive force has been studied using the two-time scale semi-classical model. It is shown that there is not any significant coupling in the linear regime. In the non-linear regime, we develop a set of coupled modified Zakharov equations which reduces to derivative nonlinear Schrodinger equation (DNLS) under steady state limit. The travelling wave solution of DNLS possesses the kinky/cusp solitons. These equations are also analyzed numerically to investigate the conditions for the significant coupling between the electron-lattice ion coupling employing the standard parameters for n-type piezoelectric semi-conductor plasmas.

P14. Plasma-driven electrochemical reduction of CO_2

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At a rate of over 30 billion tons per year, carbon dioxide (CO_2) represents one of the largest sources of human waste. At the same time, this CO_2 presents itself as a cheap, nontoxic and highly abundant carbon source, and if effectively activated, can allow for carboxylation of organic molecules. Therefore, fixation of CO_2 into organic molecules is an area of increasing interest and offers an environmentally sound alternative to conventional storage solutions. Currently, the greatest obstacle for establishing industrial processes based on CO_2 as a raw material is the large energy input required to activate CO_2 and the frequent need for expensive catalysts.

From a chemical point of view, reduction of CO_2 simply requires an electron donor and in principle, electrons can be provided by a plasma. In this work, we have developed a DC plasma reactor to investigate the feasibility of plasma-driven electrochemical reduction of CO_2 and demonstrated that carboxylation of both alkenes and alkynes is possible in a flow reactor operating at atmospheric pressure (Fig 1).

The system utilises DC plasma jets that act as a source of electrons to electrochemically drive the carboxylation of alkenes present in a flowing solution saturated with CO_2. Using Gas Chromatography Mass Spectrometry (GCMS), we show that CO_2 is selectively incorporated into the alkene *trans*-stilbene to form 2,3-diphenylpropanoic acid. The efficacy of the process depends on the plasma conditions and current efficiencies of up to 80% have been observed to date.

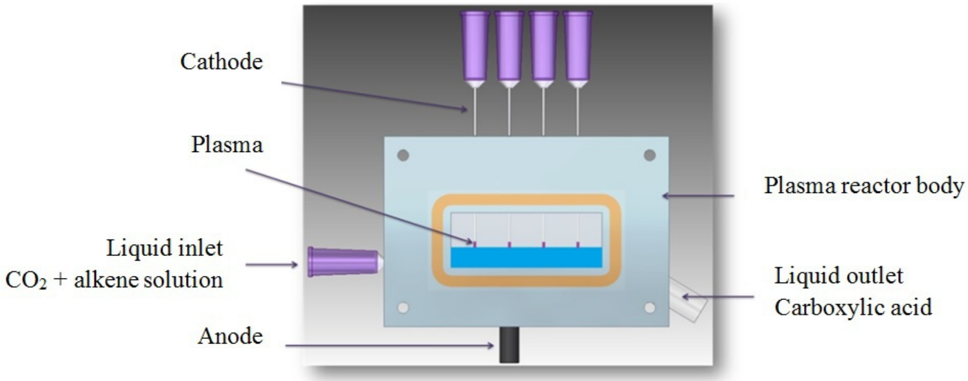

Fig. 1: Schematic of the continuous flow plasma reaction cell for carboxylation of alkenes and alkynes.

P15. Enhanced fuzzy tungsten growths due to tungsten deposition

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A concern for material research in the nuclear fusion community is the production of surface nanostructures, known as fuzz, on metals like tungsten [1] caused by their interaction with helium plasma.The future fusion reactors ITER and DEMO will feature regions of tungsten [2] and helium is produced as a by-product of the fusion of isotopes of hydrogen, therefore interaction between helium ions and tungsten components are inevitable. Due to the likelihood of fuzzy tungsten production in ITER [2], and the alteration in physical [3] and optical properties [4] of tungsten due to fuzz growth, fuzz has become a concern for the safe operation of future experimental fusion devices.

Recently the effects of tungsten deposition on to a fuzzy tungsten surface have been investigated. It has been reported that fuzz growth is enhanced in the presence of deposition, producing larger fuzzy structures including nano tendril bundles (NTBs) [5]. In this current study we recreate a range of helium ion energies (50 – 140 eV) and surface temperatures (1050 – 1150 K) predicted for the ITER divertor, and expose tungsten samples to DC helium plasma inside a magnetron device. During the exposure we co-deposit material from a target inside the magnetron on to samples which are transitioning to fuzz. Scanning electron microscopy (SEM) of the tungsten surfaces revealed fuzzy tungsten and NTBs growing on the surface. Interestingly similar fuzzy structures were seen on molybdenum surfaces, another material to feature in fusion devices [6], after treatment in the magnetron. The fuzzy tungsten samples produced within the magnetron are then compared to fuzzy tungsten samples produced in the linear plasma device NAGDIS II at Nagoya University. In that device a high density (10^{19} m^{-3}) DC helium plasma is produced but without any deposition. Through SEM analysis of the fuzzy samples produced, we make comparisons between a deposition environment (magnetron) and a deposition free environment (NAGDIS II) to see how deposition affects the overall thickness of fuzzy tungsten produced.

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[4] S. Kajita et al, “Degradation of optical reflectivity of in-vessel mirror materials by helium bombardment,” *J. Nucl. Mater.*, 417, 1–3, 838–841, 2011.

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P16. Plasma cathode electron beam for high-integrity processing

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This project seeks to optimise the design of a hollow cathode as a source for electron beams. Conventional thermionic electron sources suffer from changes in emissivity due to operation, as the thermionic material wears and distorts. This eventually requires the thermionic material to be replaced every few hours in industry, along with lengthy acceptance testing. The main advantage of a plasma electron source is a much greater lifetime and more consistent beam quality, which reduces maintenance and offers better quality in additive manufacturing, welding, and surface modification.

The low-pressure range used in this setup (~ 1e-1 – 1e-2 mbar) introduces kinetic effects which become difficult to analyse, and hence a computational approach with experimental verification was chosen. The particle-in-cell (PIC) simulation method was chosen to capture these kinetic effects.

A diagram of a hollow cathode integrated into an electron beam machine is shown in Figure 1. There are three distinct physical regions of interest: i) the electron source; ii) the gas plume; and iii) the beam acceleration region. For now, the research will focus on the hollow cathode only, and then the gas plume region will be incorporated into the model.

Initially, a basic model of a cylindrical hollow cathode was studied using the software XOOPIC [1] and an ideal current source. Having followed the well-known stability conditions for PIC from literature, an additional condition for the current resolution helped in obtaining stable simulations. Some initial results include the pressure dependence for secondary electron emission coefficient gamma_se = 1, and the dependence on gamma_se. Currently, gamma_se has been fixed to a more realistic value of 0.2 and simulations are being conducted of a more complicated hollow cathode setup used in experiments.

Experimentally, pressure measurements within the plasma chamber and current-voltage curves have been conducted. The pressure measurements showed good agreement between different hollow cathode geometries. The current-voltage curves will be used for comparison with simulation. The current-voltage characteristics showed significant heating of the cathode, which may be due to ion bombardment and the fact heat is not dissipated away easily from the cathode.

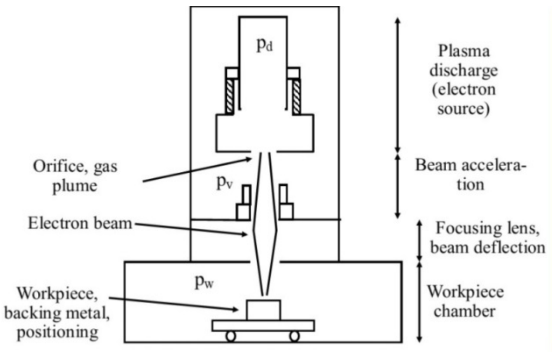

Fig. 1: Schematic of a plasma cathode electron gun used for materials processing. p_d, p_v, and p_w are the pressures of the plasma discharge, vacuum, and working chamber respectively, where p_d >> p_v and p_v ~ p_w.

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P17. Plasma-driven Epoxidation Using an Atmospheric Pressure Plasma Jet

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Non-thermal plasmas operating at atmospheric pressure open the possibility of novel processing of liquids that were not possible in conventional vacuum systems due to vapour pressure limitations; and these can be used for novel chemical synthesis processes. Particularly exciting are plasma-driven processes in which one has the potential of eliminating waste streams. This is the case of many existing oxidation processes. For example, the widely used oxidant oxone produces ~25 kg of waste per kg of oxygen transferred, whilst plasma-driven oxidation has the potential to completely eliminate this waste stream (Figure 1).

In this study, we focus on plasma-driven epoxidation, i.e. the formation of epoxides from alkenes. Epoxides are key building blocks in organic synthesis and important intermediates in the preparation of many natural products. Conventionally, epoxides are prepared by reacting alkenes with sacrificial oxygen donors. Notwithstanding recent advances in the field of catalytic epoxidation, the ultimate scheme for synthesising epoxides is the direct reaction of alkenes with atomic oxygen, as this would require no sacrificial material, no catalyst and produce no waste stream. It is well-documented that oxygen containing plasmas can produce significant amounts of atomic oxygen and that atomic oxygen readily dissolves into aqueous solutions where it can reacts with organic substrates.[1]

In this study, atomic oxygen is generated in a He/O_2 plasma jet and it is shown that atomic oxygen can react with dissolved trans-stilbene to form epoxide. Although further work is required to increase yield and selectivity of the process, the results show the potential for a waste-free plasma-driven flow epoxidation process. In addition to its synthetic value, selective epoxidation of alkenes could also provide a new means for the quantification of atomic oxygen in atmospheric pressure plasma systems.

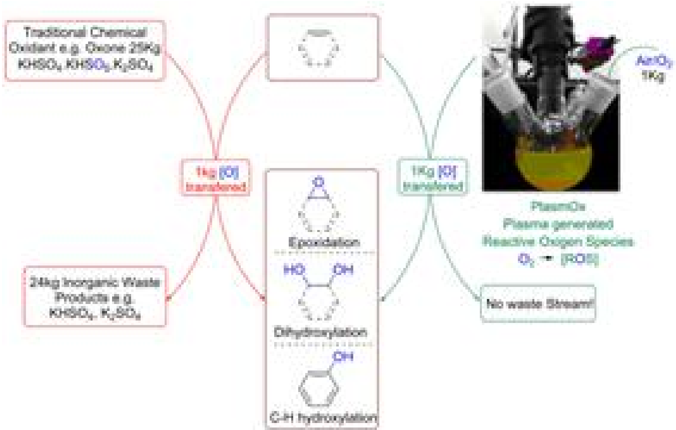

Fig. 1: Comparison of traditional chemical oxidation (left) and a plasma-driven oxidation process (right).

[1] Benedikt J et al. 2018 Phys. Chem. Chem. Phys. 20 12037–42

P18. Laser spectroscopic characterization of corundum crystal plasma

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In the present work, spectroscopic studies of the plasma produced by the fundamental (1064 nm) and second (532 nm) wavelengths of a Q-switched Nd: YAG laser at the surface of corundum crystal (Al_2O_3–Ti^{+3}) are presented . The transitions (4d $^2D_{3/2} \rightarrow$3p $^2P_{1/2,\ 3/2}$) at 256.79 nm and 257.50 nm, (5s $^2S_{1/2} \rightarrow$3p $^2P_{1/2,\ 3/2}$) at 265.24 nm and 266.03 nm, (4s $^2S_{1/2}\rightarrow$3p $^2P_{1/2,\ 3/2}$) at 394.40 nm and 396.15 nm of neutral aluminum (Al I) have been used to estimate the plasma temperature (Te) and the electron number density (Ne). The plasma temperature is determined using the Boltzmann plot method and the electron number density is determined from the Stark Broadened line width. Besides, we have also studied the variation of electron temperature and electron number density as a function of laser irradiance along the direction of propagation of plasma plume.The electron temperature and the electron number density was determined along the axial position of the plume. It is observed that the spatial behavior of the electron temperature close to the target is maximum and decreases along the distance from the target, whereas the electron number density close to the target is maximum.

Experimental Setup: Briefly we used a Q-switched Nd: YAG (Quantel Brilliant) pulsed laser having pulse duration of 5 ns and 10 Hz repetition rate which is capable of delivering 400 mJ at 1064 nm, and 200 mJ at 532 nm. The laser pulse energy was varied by the flash lamp Q-switch delay through the laser controller, and the pulse energy was measured by a Joule meter (Nova-Quantel01507).

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