51st IoP Annual Plasma Physics Conference

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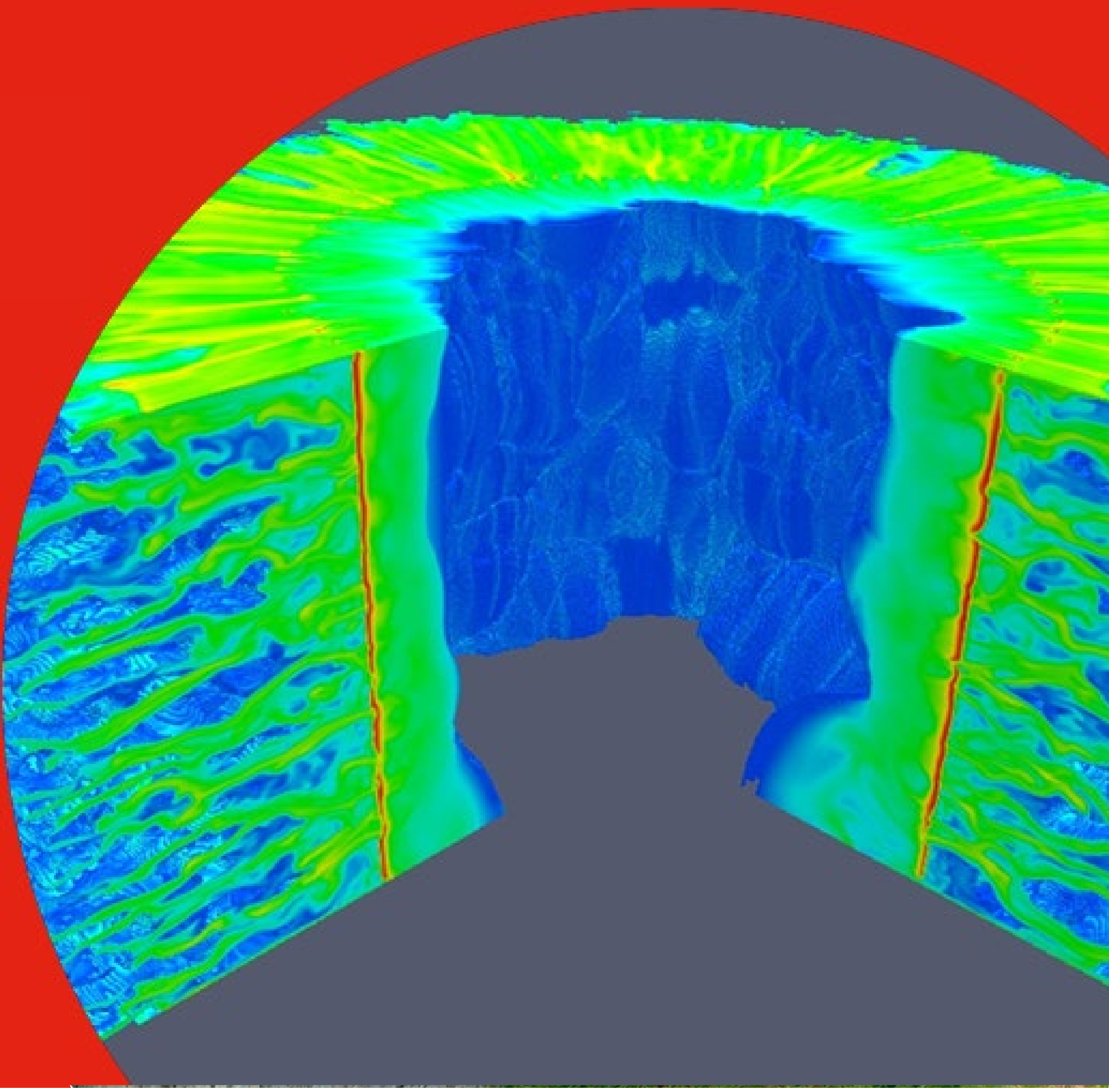

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Welcome

On behalf of the organising committee, we are pleased to welcome you to the annual IOP Plasma Physics Conference. This conference covers all aspects of plasma physics, including magnetic and inertial confinement fusion, astrophysical and space plasmas, low density and technological/industrial plasmas, low temperature plasmas, high energy density and laser plasmas, dusty and complex plasmas, plasma surface interactions, plasma applications including medical applications and plasma diagnostics.

We are delighted to announce we are working in partnership with Plasma Physics and Controlled fusion for the 51st IOP Plasma Physics Conference. This special issue of Plasma Physics and Controlled Fusion will contain papers from contributions to the 51st IOP Plasma Physics Conference. The papers will represent the diverse topics discussed at the meeting and the expanding scope of plasma physics, ranging from magnetic and inertial confinement fusion, astrophysical and space plasmas, low density and technological/industrial plasmas, low temperature plasmas, high energy density and laser plasmas, dusty and complex plasmas, plasma surface interactions, and plasma applications including medical applications and plasma diagnostics.

Supporting Organisations

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Oral Presentations

A gyrokinetic analysis of turbulent transport at the edge region of a spherical tokamak

Charlie Nicholls[1], David Dickinson[1]
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Contributed Talks - Session 4, April 9, 2025, 12:40 - 13:20

Turbulence is the dominant form of confinement reducing transport occurring in tokamaks and understanding and reducing turbulence is key to successful operation of a commercial fusion reactor. In tokamaks with sufficient heating power input an edge transport barrier in which turbulence is suppressed and pressure gradients increase, known as the pedestal, is formed. This is the high confinement mode (H-mode) of operation and the properties of this pedestal are key to tokamak performance. This work aims to increase our understanding of the conditions required to access H-Mode, how the plasma pedestal height and width evolves over time and why. A linear local gyrokinetic study is performed for a MAST-U equilibrium immediately before and after the transition to H-mode, and in an established pedestal. Analysis is performed using $\hat{s}$-α diagrams to map the stability of the plasma edge, where $\hat{s}$ is the magnetic shear and α is the normalised pressure gradient; this provides insight into why the equilibrium sits at the α value it does and what instabilities drive the turbulence limiting this value. In conventional models of the pedestal the pressure gradient is often thought to be limited by the Kinetic Ballooning Mode (KBM). Here we explore the extent to which the plasma can access the second stable region of the KBM at high α and low $\hat{s}$. A relatively weakly unstable mode is found to partially block second-stability access as it extends to low shear at lower α than the KBM onset. This mode, with an onset close to the equilibrium shear and pressure gradient at the H-mode transition, could initially limit the pressure gradient until the shear drops sufficiently, thereby acting as a barrier to higher α which is passed during the transition. This methodology could lead to greater understanding of how to access and optimise pedestal performance.

Alya4fusion: A Computational Framework for Plasma Equilibrium and Electromagnetic Wave Simulations in Fusion Reactors

Hernán Domingo[1,2], Pau Manyer[1,2], Alejandro Soba[1], Daniel Gallart[1], Mervi Mantsinen[1,3]
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Contributed Talks - Session 3, April 9, 2025, 10:40 - 11:40

In the global effort to mitigate climate change, nuclear fusion emerges as a promising energy source. The complexity of fusion reactor design demands advanced numerical simulation tools capable of modelling multi-physics phenomena. The Barcelona Supercomputing Center (BSC) hosts the Fusion Group within the CASE department. To meet computational demands, the group is developing a Digital Twin for fusion reactors using Alya [1], a Finite Element Method (FEM) framework under development since 2004. Alya4fusion leverages high-performance computing (HPC) and artificial intelligence (AI) through MareNostrum 5, a pre-exascale European-funded supercomputer at BSC. Alya4fusion consists of independent yet coupled code modules. The Fusion Group has developed NEUTRO [2] and MAGNET [3], with EQUILI and EMWAVE underway. EQUILI solves the 2D Grad-Shafranov equation for tokamak plasma equilibrium using a CutFEM scheme, handling deformable domains and balancing magnetic confinement with plasma pressure. This method enables precise modelling of evolving plasma configurations. Validated through analytical cases, it has shown promising results for ITER geometry [4, 5, 6].

EMWAVE simulates wave propagation in 2D through gyrotropic media, including cold plasma and dielectrics. It accounts for finite-source and plane waves, crucial for understanding electromagnetic interactions in fusion environments. Benchmarked against ERMES [7], it has been tested with the 2nd harmonic tritium scenario, a key ICRF heating scenario in ITER [8]. Results confirm excellent wave accessibility to the plasma region. Future developments aim to extend EMWAVE to 3D domains and incorporate a hot-plasma model for radiation absorption analysis.

This work highlights advancements in EQUILI and EMWAVE, validating their application to reactor-relevant scenarios. These developments contribute to Alya4fusion's goal: an integrated, exascale-ready simulation tool for fusion reactor design and optimization. By harnessing MareNostrum 5, Alya4fusion provides a computational framework to tackle challenges in next-generation fusion reactors, supporting advancements in sustainable energy research.

Analysis of plasma density and magnetic fluctuations over the MAST-U ETB evolution

Ciaran Jones[1,2], Yasmin Andrew[1], Tom Ashton-Key[1], Eun-jin Kim[3,4], Martin O'Mullane[5,6], Terry Rhodes[2], Rory Scannell[6]
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Contributed Talk - Ciaran Jones, April 8, 2025, 11:10 - 11:35

In magnetically confined tokamak plasmas, the non-linear phase transition from the low-confinement mode (L-mode) to the high-confinement mode (H-mode) is a consequence of the fast dynamics in the edge and scrape-off layer plasma. This transition has been shown to be the result of the predator-prey-like nature of anomalous transport driven by turbulence, zonal flows, and ExB-driven velocity shear. The significant suppression of turbulence leads to the development of a sharp pedestal profile in the edge plasma pressure, followed by a substantial increase in core plasma density and temperature with an improved confinement time. Operational challenges remain with maintaining the structural integrity and plasma performance in future fusion devices operating with the H-mode. It is crucial to investigate the time evolution of the key variable dynamics that control these confinement transitions to develop a physics-based approach to H-mode operation access and control.

High-time resolution turbulence diagnostics, such as Doppler backscattering (DBS), enable the investigation of turbulent fluctuations and plasma flow velocities [1,2]. This work presents the first statistical analysis of DBS and magnetic measurements on the MAST-U spherical tokamak [3] to determine the correlation between changes in density fluctuations, perpendicular flows ($v_\perp$), and poloidal magnetic field rate of change (dB_θ/dt). The non-linear and stochastic nature of the L-mode plasma turbulence generates strongly non-Gaussian variable distribution functions. Therefore, probability density functions (PDFs) are utilised for the plasma variable time-evolution analysis over the external transport barrier (ETB) development and evolution. PDFs allow for a more complete and robust description, in particular, the statistical parameters of skewness and kurtosis, which quantify the asymmetry and structure of the distributions. Additionally, information diagnostics are employed in this study to calculate the change in the number of statistical states across dithering phase oscillations [2,4,5]. A clear correlation is observed between an increase in $v_\perp$ and suppression of turbulence, starting in the steep pedestal pressure gradient corresponding to the radial location of peak $v_\perp$. In addition, evidence of self-regulatory behaviour of the relative density fluctuations and $v_\perp$ with dB_θ/dt is observed at the forward transitions of the dithers, in agreement with recent experiment results from DIII-D [2,6].

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[6] T Ashton-Key, et al., Plas. Phys. Control. Fus. (2025) 67 025027

Anomalous Diffusion of Light Through Shock-driven Turbulence in High Energy Density Science Experiments

Stefano Merlini[1], James Beattie[2,3], Simon Bland[1], Nikita Chaturvedi[1], Jeremy Chittenden[1], Aiden Crilly[1], Dariusz Duszynski[1], Louis Evans[1], Euan Freeman[4], Katherine Marrow[1], Thomas Mundy[1], Sergio Paniego[5], Roland Smith[1], Jergus Strucka[1], Lee Suttle[1], Aurora Uras[1], Vicente Valenzuela-Villaseca[2], Sergey Lebedev[1]
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Contributed Talks - Session 1, April 7, 2025, 16:00 - 17:00

Disordered optical media, such as turbulent plasmas, exhibit complex light propagation phenomena and understanding these processes is critical for both interpreting our observations of natural systems and applying optical diagnostics in the laboratory. We investigate the anomalous diffusion of laser light through shock-driven turbulence generated by the collision of centimetre-scale spatially modulated supersonic plasma flows on an X-ray-driven platform at the MAGPIE pulsed power facility [1].

Using synthetic diagnostics together with experimental data from a laser-based imaging refractometer [2-3], we show that light scattering through turbulent density gradients follows a super-diffusive process, where the angular broadening of transmitted light scales as a power-law function of propagation depth, $\sigma_\varphi \propto L^{\gamma/2}$ (γ>1). This contrasts with classical diffusion, where the angular broadening is expected to grow as $\sigma_\varphi \propto \sqrt{L}$ (γ=1). This anomalous scaling is attributed to the presence of intermittent, spatially localised density gradients within the turbulent layer, resulting in a heavy-tailed non-Gaussian distribution of laser deflection angles.

These findings offer a new framework for understanding laser beam propagation through non-uniform plasmas, with potential applications in enhancing communication with hypersonic vehicles and advancing optical diagnostic techniques for characterising turbulence in high-energy-density (HED) plasma experiments.

[1] J. Halliday, et. al., “Investigating radiatively driven, magnetized plasmas with a university scale pulsed-power generator”, AIP Physics of Plasmas, 2022
[2] J. D. Hare, G. C. Burdiak, S. Merlini, et. al., “An imaging refractometer for density fluctuation measurements in high energy density plasmas”, AIP Review of Scientific Instruments, 2021
[3] S. Merlini, et. al., “Radiative cooling effects on reverse shocks formed by magnetized supersonic plasma flows”, AIP Physics of Plasma, 2023

Automated design via multi-dimensional radiation magnetohydrodynamics simulation

Aidan Crilly[1], Philip Moloney[1], Jasmine Ajaz[1], Chaoyi Jing[1], Harry McCarthy[1], Amy Thornton[1], Jeremy Chittenden[1]
[1]Imperial College London

Contributed Talks - Session 7, April 10, 2025, 10:40 - 11:20

The design of high energy density plasma experiments strongly relies on simulation. These simulations provide insight and guidance towards the optimal experimental set up to achieve the scientific goal. Some examples would be the laser pulse shape in inertial fusion experiments and wire number, thickness and array diameter in pulsed power wire array experiments. This design process can be time consuming, but it lends itself to automation as the task takes the form of modifying inputs and observing outputs. In this poster, we describe how modern, gradient-free machine learning techniques, namely trust region Bayesian optimisation, have been coupled to the multi-dimensional radiation-magnetohydrodynamics code Chimera. We use this novel capability to explore designs in increasing dimensionality. Hydrodynamic instabilities can only be modelled in > 1 spatial dimension. Therefore, we will observe how designs must be modified to be robust to these instabilities, via direct optimisation in the presence of these instabilities.

This research received support through Schmidt Sciences, LLC and the IAEA AI4Fusion CRP

Detachment conditions in vibrationally-resolved SOLPS-ITER simulations.

Joseph Bryant[1], Kirsty McKay[1], James Harrison[2], David Moulton[2], Kevin Verhaegh[3], Richard Bergmayr[4], Dirk Wünderlich[4], Ursel Fantz[4]
[1]University of Liverpool, [2]UKAEA, [3]Eindhoven University of Technology, [4]Max Planck Institute for Plasma Physics

Contributed Talks - Session 3, April 9, 2025, 10:40 - 11:40

Due to inaccuracies in the AMJUEL molecular charge exchange effective rate coefficient below 2 eV , the population of D2+ is under-predicted in L-mode MAST Upgrade SOLPS-ITER simulations of the Super-X divertor when compared to experiment [1, 2, 3, 4]. Note these effective rates are mass-rescaled from H to D. Plasma conditions in detachment reach very low temperatures and densities (0.1 < Te < 5 eV , ne ≲ 1018 m−3), which is caused by plasma-molecular interactions (PMIs) featuring D2+ on MAST-U. The lowered population results in decreased levels of PMIs such as Molecular activated recombination and dissociation (MAR and MAD). MAR results in recombination of D+ which lowers the ion target flux and MAD is a means of molecular dissociation; these reactions form excited D which result in radiative losses, ultimately lowering the plasma temperature enough to trigger electron-ion-recombination (EIR) [5, 6]. EIR is additional ion sink and source of radiative losses via the production of excited D, enhancing detachment further. Recently a new molecular rate dataset (X1EXT) was produced using the vibrationally-resolved Yacora-H2(X1, v) model [7, 8, 9]. This dataset was applied to an isolated divertor leg geometry in SOLPS-ITER with MAST Upgrade L-mode Super-X conditions. Below Te = 1 eV , X1EXT increases the levels of D2+. Resulting in elevated levels of MAR, MAD and EIR. When compared to the reference simulations, this results in stronger ion target flux roll-over, and larger power dissipation during detachment that are qualitatively in better agreement with trends on MAST Upgrade and TCV [5, 6].

Employing effective rate coefficients that act on the molecular ground state density results in an inherent assumption, the lifetimes of all vibrational levels are assumed to be extremely small (transport and plasma-wall interactions are ignored). This is required for numerical validity when constructing effective rate coefficients [10]. In deep detachment, this is not valid as the mean free path of vibrationally excited molecules exceeds the divertor size [11].
Vibrationally-resolved SOLPS-ITER simulations were constructed using data from X1EXT and were compared to the prior study. Resolving the transport of D2(v) results in an increase in vibrational excitation in detached regions via transport from hotter regions. This enhances electron quenching so that the levels of MAR, MAD, EIR and molecular dissociation are elevated. This further increases the power dissipation and enhances the ion target flux roll-over when compared to the effective rate simulations, providing greater agreement with the experimental trends.

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Cyd Cowley

The management of plasma exhaust is one of the most intricate and pressing challenges facing magnetic confinement fusion. Fusion power-plants like STEP may direct more heat to surrounding material than is experienced by spacecraft upon re-entry into earth; and for an economic fusion plant these materials must survive for years of full power operation. Luckily, there are many potential solutions to the exhaust challenge, and one such solution is to cleverly design the divertor, which manages the majority of plasma exhaust. Novel alternative divertor configurations are predicted to have many benefits, particularly for the operational mode known as detachment. In this talk, we will look at these benefits, and how well these predicted benefits are reproduced by high-fidelity simulations and experiments.

Dynamics related to I-phase in the spherical tokamak ST40

Alsu Sladkomedova[1], Otto Asunta[1], Peter Buxton, Aleksei Dnestrovskii, Matteo Fontana, Thomas O'Gorman, Filip Janky, Hazel Lowe, Graham Naylor, Adrian Rengle, Michele Romanelli, Marco Sertoli, Jari Varje, Elena Vekshina, Hannah Willett, Jonathan Wood, Xin Zhang
[1]Tokamak Energy

Contributed Talks - Session 6, April 9, 2025, 16:40 - 17:40

Predicting core energy confinement requires an understanding of turbulent transport and the role of zonal flows. As confinement gradually improves beyond L-mode conditions, approaching the L-H transition, the plasma can enter an I-phase — a state characterized by limit-cycle oscillations (LCOs), which arise due to periodic changes in edge transport and, consequently, in plasma profiles [1].
In this work, we present an analysis of edge plasma dynamics during the I-phase in the spherical tokamak ST40. ST40 is a spherical tokamak with a major radius of 0.4–0.5 m, an aspect ratio of 1.6, the magnetic field up to 2.1 T at 0.4 m. Auxiliary heating was provided by two neutral beams, each delivering up to 0.8 MW and 1 MW at energies of 18–25 keV and 55 keV, respectively.
In ST40 plasmas, the oscillations in the kilohertz range were observed in various plasma quantities, including the midplane and divertor visible radiation, the poloidal magnetic field, the electron density and the ion saturation current. These bursty oscillations exhibited a three-phase cycle:
1) A gradual drop in D-alpha emission (~10%) and an increase in density (~0.2%).
2) A sharp rise in D-alpha emission (~30%) accompanied by a short-scale increase in density (≤1%).
3) A sudden crash in both D-alpha emission and density.
The observed dynamics suggest periodic suppression of edge turbulent transport and improvement in confinement, consistent with LCOs. The magnetic component of the LCO exhibited a mode structure of m=1, n=0, in agreement with observations from other tokamaks [2]. Our findings reveal nonlinear interactions, indicating the presence of zonal flows during LCOs. Furthermore, the frequency scaling with edge sound speed indicates that the observed mode may correspond to a geodesic acoustic mode.

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Formation of x-ray driven rotating plasmas on MAGPIE pulsed-power generator

Katherine Marrow[1], Jergus Strucka[1], Stefano Merlini[1], Niki Chaturvedi[1], Lee Suttle[1], Thomas Mundy[1], Vicente Valenzuela Villaseca[2], Sergey Lebedev[1]
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Contributed Talks - Session 1, April 7, 2025, 16:00 - 17:00

Rotating accretion flows can be found in many places in the universe, and producing differentially rotating plasma flows in the laboratory enables the study of physics relevant to these astrophysical objects. Here, we present results from experiments on the MAGPIE pulsed-power generator characterising a stable, hollow, rotating cylinder of plasma which is formed by the off-axis collision of multiple converging, x-ray driven plasma flows with non-zero angular momentum. Using measurements including Thomson scattering, interferometry, optical self-emission spectroscopy, and fast gated cameras, we characterise the plasma parameters and rotation of this plasma. By changing the material of the targets, we investigate radiative effects on the ablated plasma.

This research is supported by the the NNSA under DOE DE-NA0004148; EPSRC and First Light Fusion under the AMPLIFI Prosperity Partnership EP/X025373/1; AFOSR under FA8655-23-1-7062; and Sandia National Laboratories.

Gyrokinetic study of TAE damping channels and energetic particle drive in spherical Tokamaks MAST-U and STEP

Noah Chulu Chinn[1,2], Ben McMillan[2], Francesco Palermo[1], Colin Roach[1], Michael Fitzgerald[1], Ken McClements[1], Sam Gibson[1], Mykola Dreval[1], Alexey Mishchenko[4], Thomas Hayward-Schneider[3]
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Contributed Talks - Session 8, April 10, 2025, 13:00 - 13:40

The toroidal Alfvén eigenmode (TAE) is an Alfvénic gap mode that, when driven unstable, can cause anomalous energetic particle (EP) transport, redistributing energy across the Tokamak and reducing the plasma heating efficiency. The stability of TAEs is governed by the interplay of various drive and damping mechanisms, each with distinct dependencies on key system parameters. To enable predictive modelling for current and future fusion devices the global gyrokinetic code ORB5 has been used to study linear TAE behaviour.

Code diagnostics have been developed that quantify energy transfer across different species and fields, decomposing it into specific components of particle motion, such as parallel and perpendicular contributions. These diagnostics allow a detailed investigation of damping mechanisms in modes that would otherwise remain stable and difficult to isolate in initial-value simulations. After benchmarking these diagnostics in circular geometries, ORB5 has then been applied to MAST-U scenarios to study Alfvén eigenmode physics in a high-beta, low-aspect-ratio environment, where TAE drive and damping differ significantly from those in conventional tokamaks; strongly influencing both the linear and nonlinear dynamics.

Building on these foundations, the study of TAEs and their damping mechanisms in MAST-U provides critical insights for next-generation spherical tokamaks such as STEP. For parameter values in which STEP will operate, understanding competition effects between damping channel and drives is essential for optimising confinement and minimising EP losses in high-performance operational scenarios. The methodologies developed in MAST-U have been used as a basis for investigating TAE stability in STEP scenarios. TAEs have been identified and investigated using ORB5 in STEP-like equilibria with low beta. A scan in beta can then be performed to determine the effects of bulk plasma damping on these modes.

This work has been funded by STEP, a major technology and infrastructure programme led by UK Industrial Fusion Solutions Ltd (UKIFS).

High-k Adjustable-radius Scattering Instrument and synthetic diagnostic development for MAST-U

Dr David Speirs[1], Juan Ruiz-Ruiz[2], Maurizio Giacomin[3], Valerian Hongjie Hall-Chen[4], Alan D. R. Phelps[1], Roddy Vann[5], Peter G. Huggard[6], Hui Wang[6], Anthony Field[7], Kevin Ronald[1]
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Contributed Talks - Session 7, April 10, 2025, 10:40 - 11:20

Plasma turbulence on disparate spatial and temporal scales and associated cross-field particle / heat transport plays a key role in limiting the level of confinement achievable in tokamaks. The development of reduced numerical models that accurately predict cross-scale turbulent interactions is essential for understanding and maximising confinement. Such models require experimental turbulence data at both electron and ion scales to inform development. In this paper, we propose a novel, mm-wave based collective scattering diagnostic for measuring normal and binormal high-k (electron-scale) turbulence in the core and edge plasma of MAST-U. This will complement the existing ion-scale BES (beam emission spectroscopy) diagnostic, yielding core and edge measurements at both electron and ion scales whilst providing full spatial coverage under all operating conditions. We present detailed hardware specifications along with beam-tracing calculations predicting the spatial and wavenumber resolution of measurement. We also perform analysis of the instrument selectivity function computing the localisation and sensitivity of measurement accounting for both magnetic pitch rotation with radius and spatial overlap of the incident and scattered Gaussian beams. A synthetic diagnostic framework is presented combining CGYRO predictions of ETG turbulence for a sample equilibrium with beam tracing data, mapping the instrumental wavenumbers to field-aligned coordinates and predicting the scattered power spectrum. Baseline specifications of the diagnostic include an operating frequency of 376 GHz, a source power of ~100mW and a normalised turbulence wavenumber measurement range of $k_\perp\rho_e$ = 0.1 – 0.6 where $k_\perp$ is the binormal turbulence wavenumber and ρ_e the electron gyroradius.

Kinetic modelling of heat-flow and transport in anisotropic plasmas using particle-in-cell codes

Dr Adam Dearling[1], Christopher Arran[2], Jeremy Chittenden[1], Martin Read[3], Christopher Ridgers[2], Nigel Woolsey[2]
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Contributed Talks - Session 6, April 9, 2025, 16:40 - 17:40

Heat-flow is crucial in plasmas with extreme temperature gradients, such as those found in laser-plasma experiments, relativistic jets, and tokamak divertors. Transport effects, including heat-flow, are driven by anisotropies within the plasma's distribution function. As anisotropy increases, the system moves away from local thermodynamic equilibrium (LTE), and fluid models, which assume only small deviations from a Maxwellian distribution, fail to capture transport effects accurately.

In this work, we show how kinetic modelling using particle-in-cell (PIC) codes helps us understand plasmas driven away from LTE. While traditionally used to model collisionless phenomena, the inclusion of binary collision operators in PIC codes allows the study of collisional transport processes. Since PIC codes do not assume a specific form for the distribution function, they are well-suited to problems with significant anisotropy. The regimes considered here are common in high-energy-density systems, such as inertial confinement fusion, where the mean-free-path of heat-carrying electrons and ions can exceed the plasma length scale, leading to non-local heat-flow.

Laboratory Experiments of Alfvén Wave Interactions through the Transition from the MHD to the Kinetic Range

Samuel Greess[1], Chris Chen[1], Mel Abler[2], Seth Dorfman[2], Steve Vincena[2], Marvin Drandell[2]
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Contributed Talks - Session 6, April 9, 2025, 16:40 - 17:40

Turbulence is ubiquitous throughout different space plasma environments, facilitating the cascade of energy down to smaller and smaller length scales. That said, the different parameter regimes at which these plasmas exist have a significant effect on the way the cascade develops. Though in-situ measurements can provide a wealth of knowledge about the properties of space turbulence, they are limited by their spatial extent relative to the plasma environment and their reproducibility. Laboratory plasma experiments like those run on the LArge Plasma Device (LAPD) at the University of California-Los Angeles can provide insight complementary to satellite data. The space plasma turbulence group at Queen Mary University of London (QMUL) has run Alfvén wave experiments on LAPD studying weak and strong interactions at a range of $k_{\perp} \rho_s$ values, from very small (MHD limit) up to order unity (kinetic limit). The change in the properties of the drive waves and their interaction products between these limits has been quantified via detailed measurements of magnetic and electric field fluctuations in multiple different counter-propagating wave configurations. Further data runs allowed for an analysis of the residual energy- and cross helicity-dependent properties of the interactions. With this experimental setup, the fundamental physics of the three-wave interaction can be studied in detail while minimizing the impact of other solar wind phenomena.

Funding via the UK Research and Innovation (UKRI) Future Leaders Fellowship (FLF).

Numerical studies of the electro-thermal instability in MagLIF relevant conditions

Nikita Chaturvedi[1], Helene Biragnet[1], Joshua Lim[1], Aidan Boxall[1], Jeremy Chittenden[1]
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Contributed Talks - Session 5, April 9, 2025, 15:00 - 15:40

The MagLIF (Magnetised Liner Inertial Fusion) platform is one of the leading approaches of magneto-inertial fusion, and is routinely fielded on Z, the world's largest pulsed-power generator. Here, a metallic 'liner' containing deuterium fuel is rapidly imploded using Z's 26 million amperes of current, leading to fusion conditions. Additional components include a laser preheat to ionise the fuel, and external field coils that generate >10 T axial magnetic fields to suppress thermal conduction losses.

A key limitation to achieving the yields predicted by 1D simulations is the MRTI (Magneto-Rayleigh Taylor Instability) that grows on the liner surface and penetrates the inner surface, thereby disrupting the fuel column. Notably, the MRTI is observed to be helical in the presence of the axial field, although the reason for this helicity is still unclear. There are multiple hypotheses regarding the seed of this instability, one of which is the ETI (Electro-Thermal Instability). The ETI is a feedback loop between a material's conductivity dependence on temperature and Ohmic heating. Assuming an axial current, the ETI occurs when resistive inclusions in the liner forces the current path to deviate further and further around the inclusion. This eventually leada to azimuthal striations along the metallic liner, acting as a seed for the MRTI.

This talk describes simulation efforts using the Gorgon magnetohydrodynamics code to systematically investigate the ETI. These include simulations of single defects to study the ETI in isolation, simulations of multiple defefcts to study the correlation between defects that might seed the large scale structures observed in MagLIF experiments, and simulations with applied axial fields to investigate the helicity. Finally, synthetic x-ray radiographs of full-liner calculations are presented to compare against experimental results.

Production of plasma activated water and effects on lettuce (Lactuca sativa) seed germination and seedling growth

Professor Liutauras Marcinauskas[1], Mindaugas Aikas[2], Emilija Jankaitytė[3], Lina Ragelienė[3], Rolandas Uscila[2], Andrius Tamošiūnas[2], Laima Degutytė-Fomins[3], Zita Naučienė[3], Rasa Žūkienė[3], Augustė Judickaitė[3], Vida Mildažienė[3]
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Contributed Talks - Session 8, April 10, 2025, 13:00 - 13:40

The gliding arc discharge (GAD) plasma and spark arc discharge systems were developed for production of plasma-activated water (PAW). The air and air-nitrogen gases plasma were used for PAW generation using the GAD. The flame-emission and acousto-optic emission spectrometers were used to determine the composition of air and air-nitrogen plasmas. It was obtained that the N_2, N_2+, NO and O particles were the main species in generated plasmas. The variation of the GAD plasma parameters (voltage, frequency, gas flow rate) allows to control the composition of air and air-nitrogen plasma. The spark discharge was produced in water at atmospheric pressure. The dependence of physico-chemical properties of PAW obtained from tap water, deionized water, and deionized water supplemented by salts on variation of treatment protocols was investigated. The electrical conductivity, pH, concentrations of nitrates and H_2O_2 in the generated PAW depended on the type of used water, the type of plasma discharge, treatment duration and the plasma discharge parameters. The effects of PAW on seed germination in vitro, and effects of seedling watering and leaf spraying with PAW on plant growth and leaf biochemical composition were compared in two lettuce cultivars - green 'Perl Gem' (PG) and red 'Chervanek' (Ch) cultivated under different conditions. PAW slightly stimulated germination in vitro of PG but not Ch seeds. PAW watering and leaf spraying did not affect growth on PG seedlings for 15 days in a green house, but leaf spraying (not PAW watering) increased biomass of Ch seedlings by 21%. Significant effects PAW watering or leaf spraying on growth of lettuce were not observed after cultivation for 6 weeks in a field, however leaf spraying significantly increased antioxidant activity and amounts of phenolic compounds in Ch leaves.
Acknowledgement: This work was supported by the Research Council of Lithuania under Grant S-MIP-23-8.

Proton beam divergence measurements from radiation pressure driven shock acceleration

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Contributed Talks - Session 3, April 9, 2025, 10:40 - 11:40

Laser-plasma ion acceleration is a well established field of research, with several mechanisms being exploited to produce particle beams with high energy and short bunch lengths. These characteristics are well suited to many applications, among them, FLASH radiotherapy.
One of the most promising acceleration techniques used is radiation pressure acceleration (RPA), which turns into collisionless shock acceleration (CSA) when thermal effects become relevant.
Scaling laws show that both the vector potential of the laser, and the critical density of the plasma scale favorably with the laser wavelength. These considerations make the long wavelength (9.2µm) and high power (a0>1) CO2 laser at the Brookhaven National Laboratories (BNL) the ideal choice for exploring and pushing the boundaries of RPA using gaseous targets.
The work carried out by the Imperial College group at BNL has demonstrated steady ion production, albeit with low energy, in the scenario where the laser's main pulse interacts with the gas jet from a supersonic conical nozzle.
Significant gains in the ion energies were obtained when employing the laser's pre-pulse to shape the target and form spherical blast waves. This approach consistently produced low divergence, ~1MeV quasi mono-energetic ion beams. The results are backed by particle in cell simulations which give insights on the acceleration dynamics.
Thanks to a short-pulse Ti-Sapphire probe beam, it was possible to accurately image the laser-target interaction using interferometry and shadowgraphy techniques. An innovative proton spatial diagnostic was also fielded. This allowed us to quantify the divergence of the ion beams produced, while the shadowgraphs provided the electrons' divergence information. The data showed that the ion and electron divergences appear to be negatively correlated. Measuring particle divergence is a crucial first step towards optimising the coupling between beams and transport lines, which is essential for all applications of ion acceleration.

Simulating radiatively driven magnetized shock experiments using a variable Eddington factor radiation model

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Contributed Talk - Ben Duhig, April 8, 2025, 12:55 - 13:20

A set of experiments studying radiatively driven magnetized shocks [1] have been carried out at Imperial College London. Two planar silicon targets are ablated by X-rays produced by a wire array Z-pinch. This produces two counter-propagating magnetized plasma flows that collide, forming radiative shocks. The colliding flows have a quasi-2D geometry allowing for well-defined experimental data compared to more complex schemes typical of HEDP. In this work, we simulate these experiments using a radiation transport and MHD code Chimera [3] in order to investigate the sensitivity of the simulations to how radiation transport is modelled. The radiation moment equations are obtained by taking successive angular moments of the radiation transport equation. An additional expression for the radiation pressure tensor is required to close the system of equations. In this work, two closure relations are investigated. The P1/3 closure assumes a scalar radiation pressure equal to the radiation energy density while the variable Eddington factor (VEF) closure assumes the radiation pressure tensor is an analytic function of the local radiation energy density and flux [4]. The VEF closure is better suited to anisotropic radiation fields than its P1/3 counterpart as it retains some of the angular structure. Regions of the silicon targets facing the Z-pinch experience a higher intensity of incident radiation and are therefore preferentially ablated. Initial results indicate an anisotropic treatment of the radiation transport such as the VEF closure is required to capture the subsequent non-uniform ablation of the target.

Acknowledgements
This work is supported by First Light Fusion.

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Simulations of asymmetric implosions in magnetised direct drive cylindrical targets on NIF and Omega

César Freitas[1], Philip Moloney[1], Adam Dearling[1], Jeremy Chittenden[1], João Santos[2], Mathieu Bailly-Grandvaux[3]
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Contributed Talk - Cesar Freitas, April 8, 2025, 10:45 - 11:10

Applying external magnetic fields to inertial-confinement fusion implosions has been observed to improve ion temperature and fusion yield at both NIF [1] and OMEGA [2] by suppressing thermal conduction losses in the hotspot. Correctly modelling this behaviour requires the inclusion of extended MHD effects [3], but doing so could lead to improvements in experimental design and analysis in the pursuit of commercial fusion energy. Cylindrical implosion experiments are often used to analyse magnetic flux compression, as they provide a geometry that is simpler to diagnose than spherical implosions while still capturing potential effects from extended MHD terms.

Although promising, results from recent direct-drive experiments involving imploding magnetised D2 gas-filled cylinders at OMEGA [4] and NIF have fallen short of the compression ratios and yields predicted by simulations which assumed azimuthal symmetry. In this work we use the CHIMERA radiative-MHD code to explore how long-wavelength azimuthal asymmetries seeded by the laser beam geometry used at these facilities can mislead spatially integrated diagnostics into incorrectly interpreting experimental conditions.

Previous implosion simulations have assumed angular symmetry [4], but ongoing azimuthally symmetric 1D and 2D simulations with azimuthal variation appear to confirm that NIF-like laser conditions introduce a major mode-8 instability in the stagnation phase, leading to lower fusion yields due to reduced energy retention. Equivalent simulations on OMEGA also demonstrate the development of a mode-5 instability. Synthetic space-integrated proton radiography and x-ray self-emission diagnostics are used to confirm that these instabilities lead to reduced experimental compression metrics when azimuthal variations are included, which agrees with experimental analysis.

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Space Charge Compensation in Negative Hydrogen Ion Beams: A Particle-In-Cell Study

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Contributed Talks - Session 4, April 9, 2025, 12:40 - 13:20

Negative hydrogen ion sources are extensively used in particle accelerators worldwide for a variety of applications (e.g. for high-energy particle physics in CERN and in spallation neutron source facilities like ISIS) and in magnetic fusion experiments utilizing neutral beam injection for plasma heating and diagnosis. A typical problem encountered in the low energy beam transport (LEBT) region of particle accelerators is beam divergence and transport losses due to space charge effects. Space Charge Compensation (SCC) is a process that lowers the space charge of the ion beam and helps to minimize transport losses. The SCC occurs when the H- beam ionises the background gas and traps positive ions to the beam potential forming a peculiar low-density “beam-plasma”. A joint experiment-simulation campaign is currently underway to study the SCC process and the associated beam-plasma dynamics to support ISIS operations and upgrades to the facility in the negative H- ion source regions.

The SCC process is computationally investigated for a range of operating conditions using the open source, particle-in-cell (PIC) code, PICLas [2]. Simulations considering a multi-reaction framework have shown that SCC is effective in reducing the beam potential. The role of magnetic field and secondary electrons on the dynamics of the beam-plasma interactions will be examined under various operating conditions. Additionally, experiments are underway at ISIS to correlate the beam transport and light emission signals observed with the dynamics of the beam potential through time-resolved measurement of the energy distribution of the electrons repelled by the H- beam. The implementation of light emission as a PIC simulation output and a comparison between simulation and experiment results will also be reported.

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Structural & Electrical Enhancement of Radial Uniformity in Wide Aspect Ratio RF-CCP Processing Sources

Dr. Scott Doyle[1]
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Contributed Talks - Session 1, April 7, 2025, 16:00 - 17:00

Plasma-assisted manufacturing processes are critical to modern semiconductor manufacturing. Such processes typically employ fluorinated molecular species (e.g. NF3, CF4, SF6), the fugitive emissions of which represent a significant impact on the environment, as an example SF6 introduces ~23,000 CO2 equivalent warming. Enhancement of the radial uniformity in such processes enables processing wider aspect-ratio wafers, increasing the CPU throughput, and hence reducing the processing gasses required per CPU manufactured. Control of macroscopic plasma properties is therefore critical to maintaining processing quality, improving profitability, and reducing the environmental impact of such processes.

In this work, 2D fluid/Monte-Carlo simulations were employed to demonstrate and compare two methods for the control of radial uniformity in a collisional (200 Pa, 1.5 Torr argon) radio-frequency capacitively coupled discharge. This was first demonstrated by the introduction of a single toroidal cavity into the powered electrode for a 13.56 MHz discharge. Optimal conditions were found for radially wide, but axially shallow, cavities at high radii (~80% of the electrode radius). Enhanced uniformity was found to arise via indirectly enhanced secondary electron ionisation, and reduced bulk ionisation, across the wafer surface.

This control was then replicated electronically, through the application of `tailored' voltage waveforms, formed via the superposition of 5 harmonics of 13.56 MHz. Variation of the inter-harmonic phase offset enabled direct control of the spatio-temporal ionisation rate across the surface of the electrode, via modulation of the sheath dynamics. The most significant effects are observed towards the outer radial edge of the electrode, where ionisation rates and plasma density peak due to enhanced sheath collapse heating, with a more uniform distribution observed towards the centre of the electrode.

The influence of magnetic fields on the dynamics of substellar zonal flows and zonal band formation

Craig Stark[1], Declan Diver[1], Madeleine Heideman[1]
[1]University of Glasgow

Contributed Talks - Session 5, April 9, 2025, 15:00 - 15:40

The formation of zonal bands is a common occurrence in planetary atmospheres such as those observed on Jupiter and Saturn. In general, the formation of such atmospheric zonal flows is determined by the Coriolis effect and the pressure gradient force. However, If the atmosphere is significantly ionized and is permeated by a sufficiently strong magnetic field, the resulting Lorentz force could perturb the expected atmospheric flow, impacting the formation and evolution of the zonal bands. We consider a magnetohydrodynamical description of a substellar atmosphere to quantify the impact of the atmospheric magnetoplasma on the formation of the zonal flow bands. We present tentative results describing the regimes where zonal band formation is suppressed and where it is enhanced. The analysis presents the possibility to diagnose atmospheric flow speeds based on the observable number of zonal bands.

Posters

1D Simulation of a DBD Plasma Reactor: From Discharges to Reactor-Scale Kinetics

Hanen Oueslati[1], Mohamed Saadana[1], Nicolas Barléon[2], Vincent Robin[1], Elodie Fourré[3], Catherine Batiot-Dupeyrat[3]
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The production of high-value-added chemicals using DBD plasma reactors is a promising technology that has been extensively studied for many years. A major scientific and technical challenge lies in identifying the operating conditions that enhance the selectivity of target products, such as methanol or syngas in the partial oxidation of methane. Addressing this challenge requires a deep understanding of the underlying kinetic mechanisms, which can only be fully achieved by complementing experimental data with numerical simulations. However, modeling these reactors is particularly complex due to the vast disparity in characteristic time scales: plasma discharge kinetics occur on the nanosecond scale, while the overall reactor dynamics unfold over several seconds. Furthermore, the conversion rates of the desired products are often low, requiring the detection of trace species, while the reliance on outlet measurements necessitates simulating the entire reactor to enable meaningful comparisons with experiments. These constraints make accurate numerical modeling particularly challenging.
To overcome this challenge, we propose a 1D numerical strategy that incorporates experimentally measured electrical signals, such as power and current, to constrain the simulation of plasma discharges. This approach enables a more accurate representation of the plasma behavior within the reactor. Our results demonstrate that even minor variations in the global gas composition significantly influence the discharge dynamics, particularly by modifying the breakdown voltage between the reactor inlet and outlet.
With this methodology, we achieve a full reactor simulation (corresponding to a residence time of 9 s) in 1D, capturing the evolving gas composition while maintaining a constant power consumption of 5 W, consistent with experimental conditions. The proposed model not only facilitates direct comparison between simulations and experimental measurements but also accounts for the spatial heterogeneity of discharge distributions within the reactor. This numerical tool provides a robust framework for detailed parametric analyses of the reactor's kinetic behavior, offering new insights into optimizing plasma-assisted chemical processes.

3D fluid turbulence simulations of DIII-D tokamak plasmas using Hermes-3

Thomas Ashton-Key[1], Yasmin Andrew[1], Ben Dudson[2], Robert Kingham[1], Eun-jin Kim[3], Terry Rhodes[5], Zheng Yan[6]
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Results of 3D multi-fluid turbulence simulations of a DIII-D tokamak plasma using Hermes-3 are presented. Hermes-3 is a multi-component plasma fluid code based on the BOUT++ framework [1] which simulates turbulence in the edge region and scrape-off-layer of tokamak plasmas with full 3D diverted tokamak geometry.

Electrostatic L-mode turbulence simulations were performed with evolving electron and ion density, momentum, and pressure. The plasma evolves self-consistently from a given grid and input power to the core. Experimental shot #185469 from DIII-D was chosen as a basis for the simulation grid and the simulation input power was set to match the experimental value in the L-mode prior to the L-H transition. This shot has upper single null diverted geometry, favourable ion grad-B drift direction, deuterium fuel, toroidal magnetic field B_T = 2.0T, plasma current I_P =-1.0MA, major radius R = 1.72m, and minor radius a = 0.6m.

Comparison between the radial pressure profile and radial electric field structures from the Hermes-3 simulation and the mid-plane experimental measurements on DIII-D show qualitative agreement over the simulation domain, matching the L-mode radial electric field well and minimum position and L-mode edge pressure profile. The radial extent of the domain is between normalised radius $0.9<\rho<1.07$, where ρ is the normalised toroidal flux radial coordinate. Experimental measurements of turbulence and flow velocities as measured with the Doppler backscattering (DBS) diagnostic are also compared to simulated values at the magnetic mid-plane. The information geometry statistical analysis technique [2] is applied to these Hermes-3 outputs and compared to previous information geometry analysis of experimental turbulence measurements in DIII-D shot #185469 [3,4].

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A portable 250kA X-pinch for point source radiography, diffraction and absorption spectrometry

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Determining the properties of Warm Dense Matter necessitates the use of X-ray based diagnostics including radiography, diffraction and absorption spectrometry. As many experiments that produce WDM do so for only a few ns, the probing X-rays must be short pulsed, ideally with a high enough yield to produce data in a single experiment. They must also have the correct spectral characteristics – e.g. having a smooth continuum for absorption spectrometry. Such requirements act to restrict many measurements to X-ray beamlines like 3rd generation Synchrotrons and XFELs, which have exemplary capabilities, but can also have very limited time available for individual users.

At Imperial College we have been developing portable X-pinch drivers to provide X-ray diagnostics on large scale pulsed power and gas gun facilities that cannot readily take advantage of existing beamlines. We report on our latest X-pinch system, capable of currents ~250kA with risetimes of ~250ns. The X-pinch, which weighs ~100kg, is based on direct discharge of low inductance capacitors through a simple cylindrical transmission line and X-pinch load. Unlike many prior X-pinch drivers, our system can be utilized in any orientation, and requires minimal training for safe use – with no oil, water or environmentally toxic gases. It is also highly cost effective, opening up the use of X-ray diagnostics to university scale laboratories.

X-ray radiography of dense plasmas ablating from radiatively driven targets on the MAGPIE generator at Imperial College are presented, enabling density measurements in conditions where laser interferometry cannot be utilized. Initial X-ray diffraction results from simple single crystal metal targets will also be discussed, alongside the use of the X-pinch with polycapillary optics to enable large standoff distances.

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Characterisation of plasma properties of radiatively ablated thin foils

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We present the initial results and future research plan for experiments using the radiative ablation platform [1] on the MAGPIE pulsed-power generator (1.4 MA peak-current, 240 ns rise time) [2]. In this setup, the x-ray from imploding wire array z-pinches are used to generate plasma flows with a quasi-1D geometry into ambient magnetic field.
In this poster we present a modification of this platform, where we investigate the ablation of thin foil foils (e.g. Al, 2µm) of thickness comparable to the photon mean free path.
To probe the plasma dynamics, we employ spatially and temporally resolved diagnostics, including interferometry, Thomson scattering, spectroscopy and optical fast framing.
This study allows to obtain insights on the energy transport in magnetised plasmas in a strong radiation field.

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Controlling efficiency of surface fluxes in inductively coupled oxygen-argon plasmas with pulsed power deposition.

Theo Carpenter[1], Andrew R. Gibson[1], James Dedrick[1], Michel Osca Engelbrecht[1], Christoper P. Ridgers[1]
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Low-temperature oxygen-argon plasmas are an integral part of industrial semiconductor manufacturing. The flux of reactive oxygen species, oxygen ions, and argon ions from these plasmas are fundamental to the atomic scale precision for the atomic layer deposition and atomic layer etching processes used in semiconductor manufacturing. The power efficiency of the fluxes is becoming increasingly important to reduce the environmental impact of these manufacturing processes. Therefore, a deeper understanding of how plasma input parameters can be tuned to increase efficiency is vital. This work uses a 0D plasma-chemical model, with a collisional radiative scheme, to investigate the production of reactive oxygen species, oxygen ions, and argon ions, in inductively coupled oxygen-argon plasmas operated with pulsed power deposition [1]. The time-resolved and time-integrated fluxes are analysed as a function of plasma input power, pressure, the percentage of oxygen in the gas composition, repetition frequency, and duty cycle. The efficiency of generating a given flux relative to the input power is also investigated. For the parameter ranges tested, the efficiency is found to vary with power and the percentage of oxygen in the gas mixture. For a variation of repetition frequency, there is a minimal increase in efficiency as frequency increases until a maximum, where efficiency remains constant, for any further increase in frequency. However, the frequency at which maximum efficiency is reached decreases with increased input power. For a change in pressure, maximum efficiency at each power level is around 6-10 Pa, with an increase in power requiring a higher pressure to maintain maximum efficiency. The main production mechanisms that lead to the observed changes in efficiency and how they change for input power, will also be presented.

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Evolution of magnetic pitch angle with external transport barrier formation

Juan Rajagopal[1], Yasmin Andrew[1], Tom Ashton-Key[1], Sam Blackmore[2], Ciaran Jones[1,3,4], Eun-jin Kim[4,5], Martin O'Mullane[2,6], and the MAST-U team[2]
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Controlled magnetic confinement fusion is one of the most promising methods of future clean energy generation. In current toroidal magnetic confinement devices, the high-confinement mode (H-mode) offers improved plasma confinement compared to low-confinement mode (L-mode). The formation of the edge transport barrier (ETB) responsible for H-mode is thought to be related to the increasing magnetic field gradient and pitch angle as well as movement of the toroidal current density deeper into the plasma. The underlying physics behind mode transitions in tokamaks is not well understood. The gradient of the magnetic field lines, or pitch angle, is related to the ratio of poloidal to toroidal magnetic fields, $\alpha=\arctan(B_\theta/B_\phi)$. Results are presented from the first study of the evolution of the toroidal current density, J_T, and magnetic pitch angle α, profile measurements, from the Motional Stark Effect (MSE) diagnostic on the MAST-U [2] spherical tokamak, in the lead-up to and across the low to high (L-H) plasma confinement transition.

The values of pedestal region J_T and α before, at and following the L-H transition are presented as a function of core plasma density, and show clear increase in values at normalised radius $\rho = 0.8$, as the plasma external transport barrier strengthens from the L-mode, over dithering phase and in to the H-mode, for all values of core plasma density considered. Two of the density scans have been considered for an in-depth study of the J_T and α profile evolution as the ETB develops. The J_T profile is observed to peak at around 100 ms prior to the L-H transition, at a normalised radius, $\rho = 0.8$, with values ranging from 1.07 to 4.15 A cm^{-2}. The edge plasma values of α at $\rho = 0.8$ also increases prior to the ETB formation, reaching a maximum of $\alpha = 0.62$ radians at the time of transition for both shots. These results indicate that local magnetic shear in the pedestal region may contribute to suppression of turbulence and formation of the transport barrier.

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Flexible grids for complex tokamak topologies

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The divertor problem is one of the biggest ongoing challenges in the fusion energy sector. The geometry of the divertor region in magnetic confinement devices significantly influences plasma edge dynamics as well as heat and particle exhaust.1 Advanced divertor configurations, like the snowflake divertor, offer advantages in mitigating heat loads and enhancing plasma performance.2 However, simulating these geometries can be extremely challenging due to intricate magnetic structures and the complex physics of the region.
BOUT++ is a widely used open-source framework for simulating plasmas at the edge regions.3,4Its capability to handle complex divertor geometries and topologies has been limited by the current mesh, which is unsuitable for non-standard geometries. To address this, we are developing a new mesh that expands BOUT++'s ability to simulate complex divertor configurations, including the snowflake divertor. The new mesh, based on the one developped for the overture framework5, will allow users to define arbitrary geometries with flexibility and precision. The new mesh will support non-orthogonal, flexible grids5 and handle coordinate singularities and discontinuities in the magnetic field, while still allowing for parallelization. In the following six months, we expect to get the mesh working with a consistent interpolator for overlapping grids and grids with different cell sizes, both working in a parallel paradigm, and expanding the mesh into 2 and 3D.
The expanded capability to simulate complex divertor geometries within BOUT++ opens new ways of investigating advanced divertor concepts and optimizing divertor design in future fusion reactors. Ongoing work includes working on the parallelization of the flexible grid as well as interpolation between overlapping and different sized grids, and implementing guard-cell communicaton between them to help with numerical stability6. This development provides a valuable resource for theoretical and computational exploration of plasma behavior in complex divertor configurations. Understanding the behaviour and advantages of the advanced divertor geometries’ will be crucial for any fusion powerplant in the future.

Impact of Temperature Anisotropy on Longitudinal and Transverse Wave Dynamics in Unmagnetized Partially Degenerate Electron Plasmas

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Thermal temperature anisotropy plays a crucial role in the spectral analysis of waves in both laboratory and space plasmas, particularly when finite temperature effects are important. Using the linearized Vlasov-Maxwell model, we derive the dispersion relations for both longitudinal and transverse modes in an anisotropic, collisionless, homogeneous electron plasma, incorporating arbitrary levels of temperature degeneracy through the Fermi-Dirac distribution. The response functions are expressed in terms of the plasma dispersion function adapted for the Fermi-Dirac distribution. Our results are further approximated using asymptotic expansions and series approximations of the plasma dispersion function. The analysis shows that thermal anisotropy has a more significant influence on the frequency spectrum in weakly degenerate plasma regions compared to highly degenerate ones. The derived results have broad applicability, extending from laboratory conditions to astrophysical plasmas.

Information Geometry investigation of turbulence over the L-H transition on DIII-D

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The enhancement of confinement has been a major objective to create economically viable reactors in magnetic confinement fusion research [1]. A superior confinement regime, called high-confinement mode or H-mode, is marked by steep gradients in pressure, temperature, and a reduction of turbulence in the edge plasma [2]. This suppression of turbulence is attributed to the shearing of turbulent eddies due to E×B velocity shear [1]. An investigation of the L-H transition for shot #185493 on the DIII-D tokamak is presented. Plasma turbulence properties are probed with two diagnostics, the doppler backscattering (DBS) [3] and beam emission spectroscopy (BES) [4]. DBS and BES are used to observe localized or relative density fluctuations and perpendicular velocities in the edge plasma. First results from the analysis of the data from each diagnostic using the statistical framework of information geometry [5] are presented over a transition from L- to H-mode.

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Investigating Electro-Thermal Instability Growth in MagLIF

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Magnetised Liner Inertial Fusion (MagLIF) combines features of inertial and magnetic confinement to ease compression requirements, potentially reducing the cost of achieving controlled fusion. A beryllium liner filled with deuterium fuel is axially magnetised, then preheated by a laser before being imploded. The magneto-Rayleigh-Taylor (MRT) instability is a major source of implosion asymmetries, which hinder confinement and reduce yield. It has been suggested that the unexpectedly high levels of azimuthal correlation seen in MRT growths are caused by the electro-thermal instability (ETI), which arises from the dependence of resistivity on temperature.

To investigate the role played by liner defects (voids and inclusions) in the development of the ETI, we used 3D simulations generated by the Gorgon MHD code. We studied the evolution of density, temperature, current and resistivity around different configurations of defects, over a period spanning ~100 ns from the start of the implosion drive. The evolution of axial and azimuthal correlation between the defects was then investigated by varying parameters such as the size, separation and composition of the defects.

A liner wedge containing ~50 voids was also simulated to replicate MagLIF-relevant conditions. Results suggested that only voids within the outer 20% of the volume of the liner caused significant density imprints. The application of an axial magnetic field recreated the slightly angled azimuthal striations observed in experiments. However, the angle only appeared for a simulated axial magnetic field of ~100T, far greater than the 10T used in experiments. Further work is being done to resolve the observed discrepancy.

Nuclear Physics in Plasma Environments

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Nuclear Physics and Plasma Physics study phenomena at very different energy and length scales and so are usually treated as separate disciplines. However, there are a number of ways in which an inter-disciplinary approach could advance understanding in both fields. First, many plasma experiments are excellent sources of neutrons and energetic ions that can be used to study nuclear reactions. For example, Inertial Confinement Fusion experiments can be used to study 3-body light ion reactions and neutron capture reactions. Secondly, nuclei in hot plasmas can be excited by a range of nuclear-plasma interactions. The properties of excited state nuclei, such as reaction cross sections, can differ significantly from ground state nuclei. Such properties are of particular interest for Nuclear Astrophysics, since stellar environments contain significant populations of excited state nuclei, but are challenging to study in conventional laboratory experiments. Finally, analysis of Fusion experiments involves a range of nuclear diagnostics. The analysis of these diagnostics relies on the availability of accurate nuclear data. This presentation will survey the opportunities for studying Nuclear Physics in plasma environments using both experiment and theory.

Optimised Laser Pulse Shapes for Improved Yield in Shock Augmented Direct-Drive Laser Inertial Fusion

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The shock-augmented ignition (SAI) laser pulse design for direct-drive inertial confinement fusion has already shown promising results for improved neutron yield in target capsule implosion simulations. By preconditioning the plasma and timing the outwards and inwards propagating shocks such that they collide in the hot-spot region, hot-spot conditions improve for constant laser energy [1]. This work investigates the use of modern machine learning optimisation methods on the SAI pulse shape for further yield improvement in 1D radiative hydrodynamic (RHD) simulations. The success of each implosion is determined by a generalised Lawson parameter that measures proximity to ignition when no alpha heating is simulated. A Bayesian optimisation procedure, coupled with RHD code Gorgon, is applied to maximise the generalised Lawson parameter by varying the characteristic SAI dip in the pulse shape. The laser pulse dip is parameterised by a start time, width, and height, while the total energy required and end time of the pulse are kept constant. Simulations are performed at National Ignition Facility (NIF) scales and an investigation into the shock timing of both successful and unsuccessful pulse shapes is presented.

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Parametric wave scattering experiments in inductively driven plasma

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Non-linear wave coupling can develop in plasma perturbed by powerful EM waves. These effects can arise in microwave interactions in plasmas at high (fusion) temperatures and in cool plasmas, in radio propagation in the ionosphere, in the magnetospheric plasma and in laser-plasma interactions. Understanding these interactions can potentially provide useful new ways to heat plasma, to manipulate plasma conditions or to mitigate undesirable consequences induced by such coupling. Cool plasmas with critical frequencies in the low microwave range are relatively stable and relatively easier to perturb and to diagnose. We are undertaking experiments and simulations to study the effects of microwave beams propagating in such a cool plasma. A recently commissioned large scale inductively coupled plasma is used for the experiments. It is perturbed by two powerful microwave signals, a fixed tone generated by a magnetron oscillator, and a tuneable signal generated by a TWT amplifier. The variation of the strength of the non-linear sidebands caused by Raman interaction in the plasma is studied as a function of the plasma density and microwave signal parameters. Important parts of the electrodynamic are simulated by the particle-in-cell method.

Plasma Radiative properties experiments at AWE

Zachary Kenney

X-ray spectra are pivotal in the diagnosis of plasma properties experiments. Of a particular interest in the high temperature plasma physics experiments at AWE is the diagnosis of the plasma temperature and density inferred from the K-shell emission line ratios, for example the Heβ/Lyβ line ratios, and the Stark Broadening by modelling the sample material's X-ray emission spectrum [1]. Recently, K shell X-ray absorption spectra of low Z elements have been obtained from short pulse laser heated experiments conducted at the ORION high power laser at AWE [2,3,4]. We present the experimental K-shell absorption spectra obtained from such experiments using a potassium chloride (KCl) sample, as part of an experimental platform development for short pulse heated hot, dense absorption experiments [1]. AWE's Orion laser uses short pulses to induce resistive heating in multilayer foil targets. A transverse temperature gradient in the heating is exploited to produce a hot, dense gold layer that acts to backlight the KCl sample heated up to temperatures in excess of 300eV, at near solid density [1]. Theoretical models of both CH (assumed to be pure C) and KCl were used to generate synthetic spectra to compare to the KCl measurements [4]. Due to the high temperature of the KCL sample, assumption of local thermodynamic equilibrium (LTE) was investigated by using non-LTE models. AWE's average atom opacity code, CASSANDRA, was used to generate spectra assuming an LTE model and the atomic kinetics code, FLYCHK, was executed to generate a non-LTE model spectrum of KCl [5,6,7]. The KCl modelling accounted for possible gradients in the sample by combining model spectra at different temperatures.

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Radiation-hydrodynamic simulations of the Revolver ignition target

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Revolver [1-2] is a multi-shell, direct-drive inertial confinement capsule design intended to achieve ignition in optically thin DT fuel. The design utilises collisions between three concentric spherical shells at a mass ratio of 4:1 as a mechanism for amplifying the dynamic pressure from an ablator shell to an innermost pusher shell. Constructing the pusher shell from a high Z material traps radiation within the fuel cavity, lowering the ignition temperature to 2.5 keV. This occurs upstream of stagnation at low fuel convergence, limiting the growth of instabilities and mix within the fuel, making the design a promising route to ignition.

The design uses shell collisions to suppress the growth of hydrodynamic instabilities and drive asymmetries by utilising low shell convergences and symmetrisation of compression with each successive impact. However, to properly mediate collisions, the dense shells are separated by a low-density buffer medium which accelerates and decelerates them throughout the course of the implosion, making the interfaces vulnerable to the growth of Rayleigh-Taylor (RT) instabilities.

In this work, the ignition performance of the Revolver design is assessed by 1D simulations of the baseline target using the Chimera radiation-magnetohydrodynamics code [3]. These are supplemented by 2D simulations that examine the growth and suppression of RT instabilities during shell collisions and at stagnation.

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Simulating Nonlinear Phenomena of Ion Cyclotron Emission with Gaussian Process-based Active Learning

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Ion Cyclotron Emission (ICE) is an ubiquitous phenomenon in magnetically-confined plasmas. It shows potential to be used as a fast ion diagnostic as it occurs in all hot plasmas, correlates with fusion reaction rate and neutron flux, provides coverage of both the plasma edge and core driven by either fusion-born or injected ions and can be detected using existing hardware such as ICRH antennae and Langmuir probes, demonstrating a high technical readiness and avoiding the financial and engineering costs of dedicated ion diagnostics. ICE measurements can reveal the spatial and velocity distribution of energetic ion species to potentially inform optimised heating strategies for tokamak plasmas.

The magnetoacoustic cyclotron instability (MCI), considered the dominant mechanism behind ICE, is a hot plasma effect driven by a resonant fast Alfven wave near energetic ion cyclotron harmonics. While MCI observations broadly align with linear theory, some features in experimental spectra only arise in the nonlinear phase of the instability. Plasma parameters are scanned across tokamak-relevant domains using EPOCH, a mature particle-in-cell (PIC) code used to model plasma phenomena in the fully kinetic 1D3V regime. This provides a rich dataset on which to perform uncertainty quantification (UQ) techniques, which can optimise experiments across vast parameter spaces and provide evidence for the limitations of linear models. Investigating methods for augmenting computationally cheaper linear simulations with nonlinear information would accelerate development toward both diagnostics and efficient tokamak heating systems.

Gaussian Processes (GPs) provide powerful and inherently-probabilistic surrogate models for spectral features. An active-learning-based approach with GPs is used to probe resolution limits of MCI activity and quantify the sensitivity of simulation parameters between spectra derived from the linear physics, accessible from lower-fidelity codes, and the non-linear physics only captured by first-principles kinetic modelling.

Strathclyde HPM (High Power Microwave) testing apparatus for dispersive CSRR metamaterial slow-wave structures

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A flexible and configurable HPM (High Power Microwave) testing apparatus is being designed and assembled at Strathclyde to facilitate the evaluation of a variety of novel CSRR [1] (Complementary Split Ring Resonator) slow wave structures for the generation of microwaves in the X and Ku bands. Such metamaterial-based slow-wave structures, a concept developed at Huddersfield, offer the potential for broadband and high-power operation, with the option to boost power output via multi-beam excitation across multiple phase-locked, resonant structures. The HPM apparatus has a modular design, comprising an electron gun with plasma-flare cathode [2] providing an electron beam at up to 100keV and 20A (200ns pulsed) with minimal pitch factor $\alpha = v_{perp}/v_{parallel}$. The high-voltage pulsed-power system comprises an inverting double-Blumlein coaxial cable pulser [3] triggered by a Thyratron gas discharge switch via a midplane spark-gap. A core interaction waveguide diameter of 8.2cm is used, accommodating the insertion of coaxial CSRR metamaterial structures for evaluation of slow-wave coupling. We present the results of detailed numerical simulations conducted to parametrically optimise the anode-cathode geometry, using the particle trajectory solver and Child-Langmuir [4] space-charge limited emission model in CST Particle Studio. Details of the experimental commissioning are also presented in preparation for CSRR test experiments with the optimised anode-cathode geometry and associated confining axial magnetic field profile.

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The Influence of Electric Field on Power Flow Current Loss

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Pulsed power capable of greater than 50 MA peak current is essential to a wide range of research, including fusion ignition. Unfortunately, significant power losses are observed at very high current densities, such as on the inner Magnetically Insulated Transmission Line (MITL) of the Z Machine. Further, these losses increase nonlinearly with increasing peak power. The mechanisms are poorly understood; simulations suggest everything from warm dense matter ablation to hydrogen desorption. To develop a better understanding of power loss in the MITLs of high-power machines, it is crucial to conduct scaled experiments in smaller facilities. However, in university facilities (typically ~1 MA peak current), it is difficult to reproduce the heating rate, current density, electric field, and magnetic diffusion time found on the inner MITL of the Z Machine.

A novel approach called the "hairpin" has been tested on the MAGPIE driver at Imperial College. A ~3 mm stainless steel wire is shaped to have a narrow parallel section and an inductive loop at the top. By changing the size and shape of the hairpin, the magnetic and electric fields and current density in the experiment can be adjusted. Experimental data shows electric fields approaching 1 GV/m and magnetic fields on the order of 100 T can be produced. A significant event occurs around 100 ns, before peak voltage (~120 ns). This event is associated with an inflection in dI/dt, the cessation of hard X-ray emissions, and the onset of optical emission from the electrodes. This may be a result of a very late onset magnetic insulation, or of some other physics. Plasma outflows from the electrodes, along the magnetic field lines, are observed later in the experiment. Lastly, nominally identical experiments with different electric fields were conducted, yielding insights into the importance of electric field to loss current mechanisms.

The optimization of low-voltage capillary Z-pinches for maximizing 46.9-nm Ar8+ laser energy

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The capillary Z-pinches powered by a high-voltage (0.1 - 0.8 MV) Marx generator are widely used for excitation of the Ne-like argon lasers operating at a wavelength of 46.9 nm. We recently developed a 46.9-nm Ar8+ laser pumped by a fast (T/2 = 30 ns), low-voltage (U = 35 - 45 kV) capillary Z-pinch that does not require a Marx generator (AIP Advances 14, 025048 (2024)). The laser operates by employing a C-C electrical circuit along with a magnetic switch compressor, a setup commonly used for the excitation of a standard TEA XeCl-excimer laser. The excitation system's remarkably low voltage makes the laser portable, affordable, and easy to use. Unfortunately, the laser produces 46.9 nm light pulses with relatively modest energy, up to 4 μJ. This study identifies the parameters associated with low-voltage capillary Z-pinches that facilitate the enhancement of laser energy. The parameters were determined utilizing an electrical circuit interface of the COMSOL Multiphysics linked to a one-fluid, two-temperature, one-dimensional magneto-hydrodynamic model of capillary Z-pinch, along with the use of an atomic kinetic code and a ray tracing code.

Tokamak Magnetic Equilibrium Self-consistency Optimisation for Enabling Study of Resistive Wall Mode Stability Properties

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A key challenge in the design of high performance tokamaks suitable for energy production is the Resistive Wall Mode (RWM)[1,2], a branch of the External Kink Mode involving a resistive wall within the no-wall limit.

The study of the RWM for Tokamak design and control involves the use of 3D simulations. Even MHD free-boundary codes such as JOREK typically take hours to time-evolve the plasma for challenging geometries such as STEP[3]. Incorporating kinetic effects, required to fully capture the stability properties of the RWM, as well as studying other pertinent phenomena for design and control, takes this to days.

Efficient design depends on quantified uncertainties, while control systems need to operate in real-time. A growing area of research to enable improved design and control involves the building of surrogates[4] that are faster to evaluate than simulations they are trained on while naturally quantifying uncertainties.

To reduce the number of simulation runs required to train surrogates, global sampling strategies are essential. This work lays the groundwork for automatic implementation of such sampling strategies for STEP geometries by providing an efficient means to take an under-specified equilibrium - leaving the choice of FF' profile free - and guide it towards a self-consistent definition with desired physical properties.

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Wave modes and gravitational instability in degenerate quantum plasmas including radiation pressure and viscoelastic effects

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The wave modes and linear Jeans instability in the ultra-relativistic degenerate strongly coupled quantum plasma (SCQP) have been studied using the quantum hydrodynamic fluid description considering the influence of radiation pressure and uniform rotation. The modified equation of state is considered in the fluid model, which includes the effects of radiation pressure of degenerate, ultra-relativistic and weakly coupled electrons and non-degenerate strongly coupled ions. Applying the normal mode analysis, a modified general dispersion relation is analytically derived and examined in the transverse mode and longitudinal mode of propagation in hydrodynamic and kinetic limits. The Jeans instability criterion depends upon the characteristic wave speed of the system modified due to radiation pressure, electron degeneracy pressure, and ion gas pressure. For an infinitely conducting fluid, the Alfven speed is noticed to intervene in the instability condition and modify the critical Jeans wavenumber in transverse propagation. The graphical illustrations show that the growth rate of Jeans instability in the kinetic limit is significantly reduced due to the prominent role of radiation pressure, compressional viscoelastic effects, electron degeneracy pressure, plasma rotation and quantum corrections. The dispersion properties of wave modes and linear instabilities are analyzed in various limiting cases of interest. The present theoretical results have been applied to understand the gravitational collapse of white
dwarfs, and it is observed that white dwarfs with a perturbation wavelength larger than Jeans length $\lambda = 1.7*10^5$ km are gravitationally unstable.