- ***Grant Reference***: EP/X025373/1 - **Inertial Fusion Energy: Optimising High Energy Density Physics in Complex Geometries**
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- ***University Lead***: Simon Bland of Imperial College London.
- **Project Manager**: Claudia Gonzalez of First Light Fusion.
- ***Partners***: First Light Fusion, Machine Discovery, Imperial College London, the University of Oxford, and the University of York.
- ***Co-Is***: Jeremy Chittenden, Sergey Lebedev, Omar Matar, Roland Smith (Imperial); Nigel Woolsey, Chris Ridgers, Andrew Higginbotham (York); Gianluca Gregori, Sam Vinko, Daniel Eakins (Oxford); Bijan Kiani (Machine Discovery).

Summary

Our Partnership aims to solve key scientific challenges underlying a new Inertial Confinement Fusion scheme employing a single sided, planar shockwave drive. The technique, pioneered by First Light Fusion, uses novel geometries to amplify and converge shockwaves within a fusion target, and could overcome many power plant engineering issues, enabling commercially viable fusion energy. However the targets utilised are significantly more complex than commonly used fusion systems that employ spherically symmetric drives[i]; hence new theory and simulations validated by quantitative experiments are required to enable fusion yield to be optimised. In these first 6 months of the Partnership we have been building our team of researchers, have begun synchrotron based experiments exploring relevant hydrodynamic instabilities, have made improvements to our computer models and ran multiple internships.

Introduction and Background

First Light Fusion's approach to Inertial Fusion could enable cost effective fusion power production, introducing a safe, stable, baseload to the UK energy supply. However the complex target geometries utilised by First Light will result in interfaces between vastly different material pressures, densities, and temperatures, which need further exploration. Our Partnership is based upon 3 objectives:

(1) To explore heat and radiation transport and hydrodynamics relevant to First Light's targets.

(2) To perform this research across micro – macro length scales and long time scales.

(3) To simultaneously mentor final year undergraduate projects, internships and PhD students.

(1) and (2) build upon the unique skills of each partner combined in an integrated programme of theory, simulations and experiments - for instance kinetic simulations at York and Molecular Dynamics simulations at Oxford providing data for macro-scale MHD codes at Imperial College and First Light; the results of which are then compared to quantitative experiments across the Partnership optimised using Machine Discovery's algorithms. The low TRL measurements involved will find applications across the High Energy Density Science community, whilst First Light will be optimally placed to translate the research to higher TRLs in its target designs.

Project achievements: outputs, outcomes and impacts

Synchrotron experiments exploring growth of the electrothermal instability

Prior to the start of the Partnership, the Imperial College Team developed a novel pulsed power platform on the European Synchrotron Radiation Facility. This is used to create warm dense matter conditions (few eV temperature, dense, strongly coupled plasmas) through the explosion of metallic wires, and for driving large scale (multi-cm), high speed shockwaves[ii]. The synchrotron provides 256 frames of radiography enabling quantitative measurements of material density and dynamics.

Over the first 6 months of the Partnership, improvements to the radiographic capabilities of the synchrotron enabled micron level measurements of the electrothermal instability. The explosion of a wire embedded in a dielectric is the basis for many measurements of electrical conductivity in warm, dense conditions. Such measurements have typically assumed the wires to undergo uniform expansion, however initial measurements in 2019 indicated this was not the case[iii], with an electrothermal instability growing as the wire exploded due to changes in conductivity with temperature as the wire undergoes phase transitions. The new results, such as those presented in Figure 1, have enabled the development of the instability to be directly measured and for the first time allowed accurate comparison of different electrical conductivity models in our MHD simulations. The results are presently being written up as a Nature Communications article, with new experiments planned at LCLS to explore the microscopic origin of the instability.

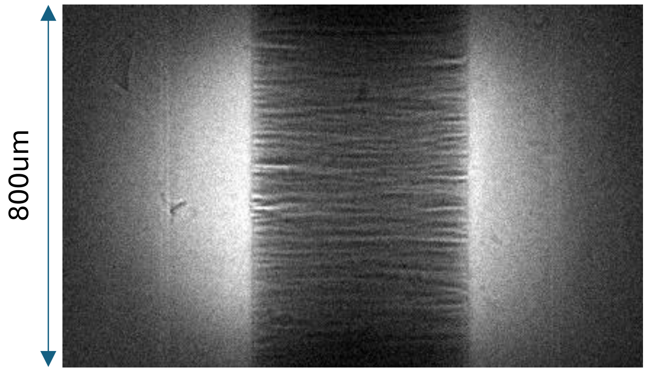

***Figure 1**. High resolution radiography of the electrothermal instability.. Right, at peak voltage through the wire*

Exploring hydrodynamic instabilities and mitigation of the RM instability

The development of instabilities such as the Richtmyer-Meshkov (RM) and Kelvin-Helmholtz (KH) on interfaces between 2 different materials is common to many areas of physics – for instance the RM instability plays a large role in supernova explosions mixing stellar material with the interstellar medium; and in inertial fusion experiments the same process can mix cold outer material from the fuel capsule with hot, compressed fuel significantly reducing fusion yield. These effects are amplified by small scale turbulence, triggered by the instability growth.

New experiments led by York University using one of First Light Fusion's 2-stage light-gas guns have aimed to develop a new shock-cloud interaction experiment to produce unstable flows and observe their transition into turbulence. In the first experimental campaign different shaped nozzles were combined with the gun to provide hypersonic gas flows over hollow plastic cylinders, with the shockwaves and instabilities in the flow observed with high speed photography and schlieren imaging (Figure 2). These experiments are analogous to laser-plasma experiments that drive strong shocks across dense metal spheres embedded in plastic - however the open geometry and larger volumes created by utilising the gas gun as a driver may enable more detailed measurements over comparatively longer (x10 hydrodynamic) timescales, albeit at lower shock pressures. The results are being compared/contrasted to hydrodynamic simulations made using OpenFoam[iv], and we plan to employ low atomic number foam targets and gas flows to attempt comparisons to astrophysical simulations.

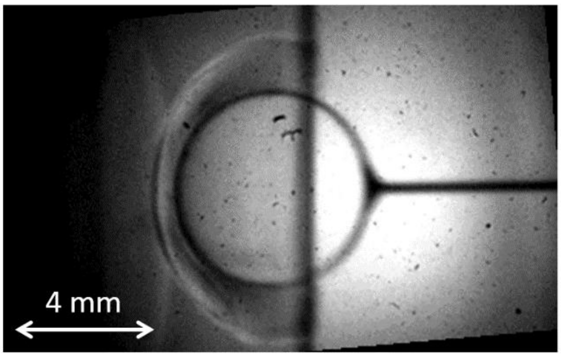

Figure 2*. A schlieren image, at 800 ns, of a gas-gun driven shock moving left to right crossing a hollow cylinder. The shock is uniform and sustained and is identified as the dark vertical feature towards the centre of this image. A stand-off shock forms on the left-hand-side of the cylinder, the cylinder subsequently crushes*

Simultaneously, a new collaboration between Imperial College and Lawrence Livermore National Laboratories has explored novel methods to mitigate the RM Instability. Researchers at LLNL utilised machine learning coupled to hydrodynamics simulations to suggest how internal shaping of a material layer could be used to introduce counter vorticity to a flow, and hence reduce the growth of instabilities at an interface[v]. The platform developed at the synchrotron enabled the first tests of these ideas – and with the internal shaping, the growth rate of the instability and the jetting from its surface became significantly reduced (Figure 3). Minor adjustments of the strength model and simulation parameters resulted in an extremely good comparison of the simulation and experimental results. The results of the experiments are now being written up for publication in PRL, with future research aimed at studying convergence effects and scaling to higher pressures and temperatures in laser driven experiments.

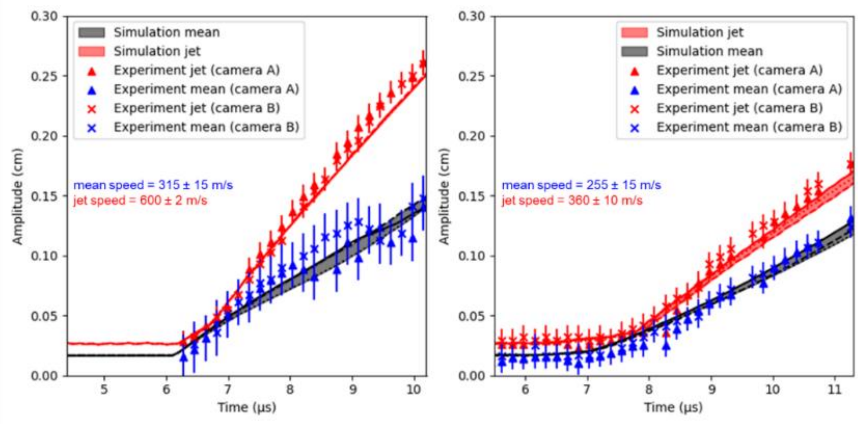

Figure 3*. Measurements and simulations of the amplitude of the RM instability and jetting. Left: unmitigated control experiments. Right: experiments including internal shaping to reduce the RM instability*

Exploring the collapse of shaped cavities driven by shockwaves

Lois Heslop, the Partnership's first PhD student, began her studies in October 2023 at Oxford. During Nov and Dec, Lois participated in a series of gas gun driven experiments at ESRF studying the effect of cavity shape on the mechanisms of cavity collapse and shock energy dissipation. Earlier numerical studies of conically shaped cavities identified three regimes of distinct behaviour which access markedly different thermodynamic conditions, and these experiments represented the first opportunity to directly study these regimes. The experiments were a success, revealing the formation of jets at low base-length aspect ratios, which were supressed as the aspect ratio increased. The results will direct XPCI measurements to inform the accuracy of our hydrodynamic codes, and ultimately improve them.

Kinetic modelling of heat transport

Thermal conduction losses between hot, compressed deuterium-tritium fuel and the high atomic number material in First Light Fusions target designs, will play a significant role in whether or not ignition is achieved, as alpha-particle heating needs to exceed all other loss mechanisms. Modelling of such losses is challenging as the extreme gradients in temperature and density result in non-local thermal transport. New research at York is utilising the UK PIC code EPOCH, to model ion-driven thermal transport. Over the first 6 months, the Partnership has seen the development of two test problems; the first examines the relaxation of a temperature gradient in a uniform hydrogen ion plasma, which has demonstrated the properties of both local and non-local transport regimes (e.g. Figure 4). The second problem examines a hydrogen-gold interface problem with a similar temperature gradient to explore how the different materials then modify thermal transport.

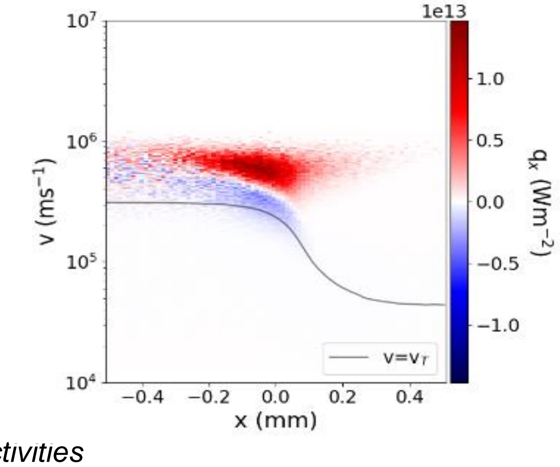

***Figure 4**. Heat-flow in velocity phase space from a hydrogen relaxation problem. Points in red correspond to the outgoing heat-flow in the positive x-direction, while blue is the heat carried by the return current in the opposite direction. The ion thermal velocity assuming a Maxwellian distribution is highlighted by the black line.*

Internship activities

Over summer 2023 several undergraduate internships made significant contributions to the Partnership. Two students at Imperial College developed new Fibre Optic based magnetic field / current sensors reducing their size from metre to cm scales whilst reduced the sensitivity of the technique to vibrations and temperatures. One student at Oxford tested initial designs for Warm Dense Matter characterization experiments with an inverse Compton source, comparing results to Monte Carlo simulations in preparation for a campaign at LCLS. One student at Imperial explored the production of electromagnetic filaments around laser spots at the Omega facility, analysing new results and helping optimise packs of CR39 and image plate for future experiments. A final student at Imperial developed a significantly better methods for tracking the interface between materials in the Imperial College Gorgon MHD code, reducing numerical artifacts that mar present simulations.

New collaborations built over the last 6 months:

i) A collaboration with Dane Sterbentz, Jon Belof and Will Schill of Lawrence Livermore National Laboratories explored new methods of mitigating the RMI instability.

ii) A collaboration with Sean Regan at the University of Rochester with the University of Oxford is exploring new neutron diagnostics.

iii) A collaboration with Jessica Shang, also at the University of Rochester, is helping Oxford prepare for experiments at LCLS to measure the viscosity of carbon foams in warm dense matter conditions using X-ray Photon Correlation Spectroscopy (XPCS).

Staff Highlights

Despite only starting in July 2023, we are rapidly growing our team. One postdoc started as soon as the project was announced, two more are about to start and five further postdocs positions are in the process of being appointed over the next three months across the Partnership. One PhD student started in October 2023, and we expect to take on seven more in October 2024, with three the following year, potentially accompanied by several leveraged PhDs. Over Summer 2023, one directly funded student internship ran with four further leveraged from UK Industrial and US funding. Each postdoc and student benefits strongly from being assigned a dedicated ‘link’ scientist/mentor at First Light Fusion, providing industrial mentoring and helping strengthen collaboration.

Hydrodynamic research by the Partnership was presented in an invited talk by Prof Bland at the ZNetUS Workshop in Jan 2024; and Dr Jergus Strucka of Imperial College has been invited to present at the 2024 Omega Lasers Users meeting. Dr Bland was promoted from Reader to Professor in Sep 2023 based on his research, including that on which parts of the Partnership are based.

References

[i] See The NIF ‘Age of ignition’ web page - https://lasers.llnl.gov/news/age-of-ignition (accessed 23/01/24).
[ii] S.P. Theocharous et al, Rev. Sci. Instruments 90(1) 013504 (2019) DOI: https://doi.org/10.1063/1.5055949 .
[iii] D. Yanuka et al, Phys. Plasmas 26, 050703 (2019) DOI: https://doi.org/10.1063/1.5089813 .
[iv] D.M. Sterbentz et al, Physics of Fluids 34, 082109 (2022) DOI: https://doi.org/10.1063/5.0100100 .
[v] Openfoam is an open source tool for Computational Flow Dynamics https://openfoam.org/ .