The UK Inertial Fusion Roadmap
2021-2035

Prepared on behalf of the UK Inertial Fusion Consortium by the Roadmap Committee
with input from the wider consortium.

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1 Executive Summary

Inertial Fusion is, along with magnetic confinement fusion (MCF), one of two extensively researched, credible, approaches to obtaining fusion energy. Fusion has the potential to provide humankind with a safe, clean, green source of carbon-free baseload electricity; if realised it would complement intermittent wind and solar sources by filling supply gaps, and provide the increase in generation capacity required to move away from fossil fuels. In contrast to nuclear fission, fusion is far safer, creates no long-lived radioactive waste, and the readily available fuel is essentially limitless. The Inertial Fusion approach to energy generation (Inertial Fusion Energy, or IFE) is fundamentally different to other fusion approaches. Importantly, IFE offers numerous potential technological advantages, and technological diversity, in an area with huge commercial potential. The recommendations and strategy set out in this Roadmap will position the UK to lead in IFE, maximising future commercial opportunities by stimulating the associated industrial and technological developments.

Inertial Fusion uses a ‘driver’ to compress matter, creating densities and temperatures exceeding those in the centre of the Sun. In the Sun, gravity holds the fusion fuel together while it burns, in inertial fusion the compressed fuel’s own inertia briefly confines it. The concept of Inertial Fusion has been successfully demonstrated in underground nuclear experiments. Thus, uniquely within fusion research, we know the principle of Inertial Fusion works.

Several inertial fusion driver technologies exist, including lasers and magnetic drivers. Significant international efforts are ongoing to demonstrate the feasibility of Laser Fusion (laser-driven inertial fusion). After a recent breakthrough, the US National Ignition Facility (NIF) is now on the cusp of demonstrating Laser Fusion energy-gain (fusion energy out/laser energy in). NIF’s energy-gain is 0.7, a 25 times increase on one year ago. This breakthrough provides concrete evidence that our understanding of inertial fusion ‘ignition’ is correct. Importantly, UK researchers have world-class expertise in the advanced science and laser technologies which can transform NIF’s result into the energy-gain required for IFE. This Roadmap sets out the UK research community’s agreed 15-year scientific and technological pathway towards IFE.

Inertial Fusion research facilities have also catalysed the rise of a new branch of science: High Energy Density Science (HEDS). Intersecting condensed matter physics, nuclear physics, astrophysics, and plasma physics, it is the science of extreme pressures, above 1 million atmospheres. HEDS now forms the foundation of a diverse range of ultra-high-tech applications which can only be realised due to HEDS unique ability to access extreme states-of-matter: from the ($70Bn/annum) technology used to manufacture the latest microchips, to next-generation particle accelerators and light-sources which are potentially 1000 times smaller than existing technologies. Laser fusion has been a key driver for laser innovation and lasers have become a core technology for society. Albeit at a lower power than required for fusion, the £13.5Bn photonics industry contributes more to UK GDP than pharmaceuticals, illustrating the commercial-potential investments in laser technology have already unlocked.

This Roadmap examines the UK Inertial Fusion and HEDS research-landscape, with a particular focus on Laser Fusion. Ongoing UK investments in magnetic fusion include the Culham Centre for Fusion Energy, JET, MAST, and STEP. While no specific UK facility, centre, or coordinated research programme, exists for Inertial Fusion, EPSRC funded research is performed at several Universities, the Central Laser Facility, STFC Rutherford Appleton Laboratory, and AWE. Fundamental physics experiments are performed at the STFC’s Vulcan and AWE’s Orion lasers, while Laser Fusion implosion experiments necessitate accessing US facilities. Despite modest funding levels, the UK is a centre of excellence for Inertial Fusion and HEDS research – it is consistently world-class and in respects world leading.

This research community-led Roadmap represents an ambitious, but achievable plan which will transform our substantial scientific, technological, and facilities expertise, into a viable path towards the realisation of IFE. This will be expedited through parallel scientific and technological development strands. A series of methodical, science-driven goals will seek to answer the key remaining scientific questions. In parallel, enabling technologies will be developed. Armed with this knowledge, the optimal route to the longer-term goal of IFE will be evaluated, then set out in detail. Throughout, we emphasise progress through: enhancing international collaborations; leveraging investments in existing facilities; working synergistically with UK IFE industry (First Light Fusion and General Fusion) and the magnetic fusion community; and growing, enabling, and diversifying the UK's world-class skills-base.

Our strategic developments will also bring about strong positive impacts to the broader UK HEDS community. This will be particularly apparent in the following areas: the provision of improved, benchmarked simulation code capabilities and physics models, synthetic diagnostics, improved experimental diagnostics and diagnostic techniques, improved UK target manufacturing capabilities, and higher energy, higher repetition rate lasers.

Broadly, the near-term strategy (to ~2025) is summarised as follows:

- **Establishing an innovative, coordinated, collaborative programme of Laser Fusion research:** the UK research community will seek to use existing facilities to demonstrate, with a significant degree of certainty, a credible, robust, route to high fusion-energy-gain.
- **Enhancing key UK technologies:** the focussed research and development of the laser drivers, implosion targets, diagnostics, data analysis techniques, facility operations knowledge, and simulation codes required for future IFE applications. These developments will best-place the UK to rapidly innovate in light of significant international developments (such as NIF achieving energy-gain > 1), whilst increasing the UK's potential for commercial gain through cutting-edge technological innovations.
- **Supporting the development and utilisation of UK assets:** we will use the Extreme Photonics Application Centre (EPAC) and Vulcan 2020 at STFC-CLF to gain invaluable knowledge regarding high-repetition rate facility operations and technologies, and to gather and utilise large datasets facilitating physics-model uncertainty quantification and simulation-code benchmarking.
- **Community building and training:** we will build upon the existing UK Inertial Fusion and High Energy Density Science research communities and UK IFE industry by enhancing collaboration through the UK Inertial Fusion Consortium, engaging with UKRI to launch a UK-wide High Energy Density Science doctoral-training scheme, and taking proactive steps to improve Equality, Diversity and Inclusion within our community.
- **Enhancing international collaboration:** we will engage with UKRI and BEIS to enhance UK-US collaborations by pursuing a UK-USA Science and Technology Agreement with a specific focus on Inertial Fusion Energy. We will also seek to foster a broader international approach to Inertial Fusion Energy collaborations including Europe and Asia.
- **UK Inertial Fusion Energy strategy:** By 2025, or earlier in the event of significant developments (e.g. energy-gain > 1, or the US establishing a significant IFE programme), we recommend BEIS or UKRI commission a review of the most appropriate path forward for UK IFE. This will enable the UK to develop a strategy commensurate with its level of ambition, to lead, or be a key partner, in the development of the science, technology, and ultimately the commercial applications, of Inertial Fusion Energy.

This near-term strategy has been designed to build upon existing UK expertise and technologies, creating the science, technology, facilities, and skills foundations required for a medium-term demonstration of sufficient energy-gain for IFE. This will enable the UK to make an informed decision on the best route to achieving fusion energy.

2 Recommendations

While we know Inertial Fusion works at large scale, NIF is now on the cusp of demonstrating energy-gain within the laboratory. The UK has a world-class research skills-base, cutting-edge laser technology and target manufacturing, world-leading fusion engineering capabilities, and a growing UK IFE industry. These recommendations build upon these foundations, with the goal of enabling the UK to rapidly become world-leading in Inertial Fusion Energy research, whilst having strong positive impacts on UK High Energy Density Science.

Research Focus

In the context of significant ongoing international investments and large Laser Fusion research-programmes, we recommend that UK-focus should be placed upon two key areas:

- **High fusion-energy-gain Laser Fusion schemes:** the pursuit of advanced, but scientifically credible, ignition schemes which are not currently prioritised internationally. These have the potential to significantly reduce driver energy, and hence system cost. This approach will maximise scientific impact, stimulate innovation and the potential for future commercialisation, with the goal of accelerating the path towards Inertial Fusion Energy.
- **The science of ignition:** increasing our understanding of the physics of ignition and the plethora of interconnected High Energy Density Science; the core scientific foundations required for a robust understanding of inertial fusion ignition. This is an area of well-established UK strength and remains a key avenue where the UK innovates, demonstrating global leadership and influence.

Funding

- **Post-graduate training:** We recommend a UK-wide training scheme for High Energy Density Science is established by the relevant UK research institutions and UKRI. This could be integrated with UK facilities and provide a PhD trained workforce in numbers commensurate with the UK's broader investments in research, facilities, and defence.
- **Laser fusion programme-grant funding:** progress in Laser Fusion requires a coordinated, collaborative programme of research with strategic direction and continuous funding. This is not provided by existing responsive-mode grants, which are high quality, but tend to be disjointed; no strategy connects projects. UK researchers should apply for programmatic funding in order to enable a strategic approach to UK laser fusion research. We recommend programmatic funding is in addition to responsive-mode grants, creating a funding increase.
- **UK-US collaborations:** the UK has extensive ongoing international collaborative research ties, particularly with the US. These are invaluable, both for research, and the substantial financial leverage that such investments may yield due to the high levels of US investment. We recommend UKRI/BEIS seek to enhance UK-US collaborations by establishing formal Inertial Fusion Energy research agreements with bodies such as DOE and NNSA.

Research Facilities and Enabling Technologies

- **Vulcan (near-term):** Vulcan remains the UK's workhorse for High Energy Density Physics research. Ongoing investments in the Vulcan laser facility are needed. We will engage with the CLF and CLF user-community to ensure particular attention is paid to improving this asset for Laser Fusion and High Energy Density Physics research. We will seek to improve the performance of long-pulse beamlines[1] by moving to third harmonic radiation and further develop beam pulse-shaping and smoothing capabilities. We will advise on future development of target areas with a particular emphasis on diagnostic provision.
- **Vulcan (medium-term):** We fully support the proposed Vulcan 2020 upgrade and welcome this as part of our strategy to strengthen UK Inertial Fusion science, it would also

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[1] 'long-pulse' laser beams have the appropriate characteristics for Laser Fusion

place the UK at the forefront of high-intensity High Energy Density Science. In addition to extreme powers and intensity, this upgrade enhances the 'long-pulse' capability and shot repetition rate. This will extend the usefulness of Vulcan long and short pulse capabilities for laser fusion research, stimulate innovation, and enable the gathering of large data sets relevant to standard and advanced Laser Fusion concepts.

- **A high-energy UK laser facility (~10 years):**
    - **Laser-driver technology:** The CLF's DiPOLE laser technology is world-leading. In order to build on this success, we recommend UKRI funds the further development of DiPOLE technology, increasing the energy to the ≥ 1 kJ level at 3rd harmonic with increased bandwidth: a prototype Laser Fusion beamline. This would establish a technological pathway towards Inertial Fusion Energy, potentially enabling the UK to become global leaders in those areas of science and technology which are particularly suitable for future power production, thereby maximising the competitive-potential for commercialisation. This would also provide the technological basis for a future higher-energy UK laser facility.
    - **A new laser-driven implosion facility:** The demonstration of sufficient energy-gain for Inertial Fusion Energy will almost certainly require a new Laser Fusion facility. We recommend undertaking a detailed evaluation of the benefits of, and potential funding-routes for a future Laser Fusion facility. Possible avenues might include as an international facility, or under a bi-lateral agreement between the UK and US.
    - **XFEL diagnosis:** The coupling of a laser-driven spherical-compression facility to an XFEL would be a transformative marriage of technologies. We recommend that consideration be given to the advantages of co-locating such facilities.
- **International facility access:** Purchasing time on the Omega laser facility is a proven access route which has greatly enhanced UK Laser Fusion research and UK-US collaborations. In the context of grant funded research, we recommend UKRI/EPSRC continue to invest in Omega laser facility experiments for laser fusion research. This would enable the UK to establish a significant Laser Fusion research programme with minimal investment.
- **Simulation-code infrastructure:** Simulations form a critical foundation for all Inertial Fusion and High Energy Density Science research. However, long-term code development is not well-matched with responsive-mode grant funding. Consequently, we recommend establishing an appropriate funding route for long-term UK simulation-code development which reflects their evolved-status into critical research infrastructure.
- **Target technology:** Current UK implosion experiments rely on purchasing US-manufactured implosion-capsules. In order to develop strategic skills, knowledge, and build upon cutting-edge UK technological and manufacturing capabilities, we recommend the CLF develops an implosion-capsule manufacturing capability. With IFE and commercial-potential in mind, novel technologies for the low-cost, mass-manufacture of implosion capsules should also be pursued.

UK Strategy

- **UK Inertial Fusion Energy Review:** We recommend BEIS or UKRI commission a UK-led review of Inertial Fusion in the context of Inertial Fusion Energy to establish a longer-term UK strategy. An appropriate timescale would be 2025, unless ignition or hydrodynamically-equivalent ignition[2] is demonstrated earlier, or, for example, the US position on Inertial Fusion Energy changes dramatically, in which case the review should be brought forward.

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[2] The creation of ignition-equivalent conditions at a sub-ignition implosion-scale

3 Equality, Diversity and Inclusivity

The UK Inertial Fusion Consortium is an inclusive network of people. We value multiple points of view and recognise that diversity drives innovation. We aim to foster collaborations and research programmes to solve questions in inertial fusion in a way that is mindful of participants' need to develop and manage their careers. We will adopt both top-down and grassroots approaches to supporting Consortium initiatives and setting objectives.

The UK Inertial Fusion Consortium encourages all members to:

- Consider equality, diversity and inclusivity (EDI) in all activities
- Respond constructively to EDI discussions at meeting
- Foster awareness of equality in decision making
- Be familiar with relevant policies and legislation through participation in EDI training within their home organisations
- Bring information on equality initiatives to the attention of the Consortium
- Celebrate EDI successes and developments

To broaden the inertial fusion community, the UK Inertial Fusion Consortium will:

- Include EDI as a standing item in all meetings
- Work to influence organisational and cultural change across high energy density physics
- Take forward suggestions to enhance equality, diversity and inclusion
- Promote a welcoming and supportive working and research culture
- Establish ad-hoc sub-groups in relation to specific areas of EDI, as appropriate
- Encourage schemes that support disadvantaged groups by any protected characteristic

The Inertial Fusion Consortium will review, annually, EDI activities associated with its initiatives and activities.

4 Creating the Roadmap

Following several national meetings of UK Inertial Fusion researchers, it was agreed that a more coordinated UK-wide approach was needed. This led to the establishment of the UK Inertial Fusion Consortium which draws members from all UK groups with a research interest in Inertial Fusion. From this, a small group, the Roadmap Committee, was tasked with drafting a 15-year Roadmap. The Roadmap Committee was: R.H.H. Scott (Chair), T.D. Arber, A.R. Bell, J. Chittenden, W.J. Garbett, P.A. Norreys, J. Pasley and N. Woolsey. We acknowledge the extensive contributions of S. Rose and G. Gregori to the Roadmap. Subsequently the Roadmap was revised based on input from the wider UK Inertial Fusion Consortium. The views expressed within this document are personal opinions and do not necessarily represent those of their institutions.

5 Background

Thermonuclear fusion (*joining* nuclei together) is the process which powers the stars. In comparison to nuclear fission (the *splitting* of nuclei), fusion has three distinct advantages for energy production: 'melt down' is not possible, radioactive by-products are of low level (and hence easily stored), and the fuel source is vast.

Two extensively researched, credible, approaches to fusion energy are being actively pursued worldwide. Magnetic confinement fusion uses magnetic fields to hold a hot, low-density plasma in place while the plasma burns quasi-continuously, somewhat akin to a conventional fire. In contrast, inertial fusion uses a driver (typically high-power lasers) to implode a hollow spherical shell containing fusion fuel. This creates density and temperature conditions exceeding those in the centre of the Sun, over a very brief duration, meaning the power source is pulsed, like an internal-combustion engine. Laser fusion is the most extensively researched type of inertial fusion, followed by magnetically-driven inertial fusion concepts.

UK-based magnetic confinement fusion research facilities include MAST and Eurofusion's JET Tokamak, while the £220M STEP project has recently been funded. ITER is being built by an international consortium with UK involvement. There are currently no UK laser-fusion-specific facilities, although a strong UK research community is actively engaged in research using the Vulcan laser (2.5 kJ of laser energy[3]) at the CLF, AWE's Orion laser (6 kJ), and increasingly through access to international facilities. International laser fusion facilities include the USA's $4Bn National Ignition Facility (2 MJ), France's Laser MegaJoule (1.4 MJ), Russia's ISKRA-6 (2.8 MJ, under construction), China's SGIII (180 kJ) and SGII (320 kJ upgrade in progress), and the USA's Omega (30 kJ). Total global investments in these facilities are of order $10-15Bn.

There is considerable certainty that inertial fusion works; firstly, the technique is employed at large scale in thermonuclear weapons. Secondly, previous AWE underground tests demonstrated that "*attempts to show the performance of small-scale fusion targets were quickly successful*". Combined with US 'Centurion-Halite' experiments, these show that the principle of inertial fusion is sound. Hence the key scientific challenge is to identify the threshold energy-scale for ignition and optimise driver efficiency, both of which depend on the detailed design.

Power production from all fusion schemes is a huge scientific and technological challenge. In the case of laser fusion, an implosion-target is first 'injected' to the target chamber centre, the lasers then fire, imploding and igniting the target. The neutrons emitted by the fusion reactions are slowed within a lithium layer, creating more tritium fuel and heat, which powers steam turbines. This process is repeated ~10 times per second. A key advantage is that lasers can be focussed from a long distance, separating them from the fusion reactions, greatly reducing neutron damage to the surrounding infrastructure. In principle, inertial fusion has the potential to achieve power production with a small system size: since the energy invested in the fuel can be as small as ~10 kJ, improvements in driver coupling-efficiency could significantly reduce system costs. Furthermore, these facilities can also explore a plethora of High Energy Density Physics (HEDP) applications, while laser and target technologies are already being spun-off into multiple applications. Finally, and perhaps most importantly, given the challenges of realising all approaches to fusion energy, combined with the huge environmental and economic rewards if it can be realised, we strongly assert that more than one approach should be pursued.

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[3] Laser energy is indicative of scale, and hence capital cost.

6 Overview of Current Research

Inertial fusion (also referred to as inertial confinement fusion, or ICF) works through the process of implosion. A spherical or cylindrical ‘shell’ containing the fusion fuel is forced radially inwards towards its centre by a driver. The most extensively investigated driver is the laser, although the use of electrically induced magnetic fields created by a ‘z-pinch’ are quite widely investigated. Alternative methods include gas guns and plasma guns.

The driver acts to compress the fuel, increasing its density by more than 1000 times. In the most extensively researched ‘central hotspot’ approach to inertial fusion, a small mass of hot, low density fuel (the ‘hotspot’) is created at the centre of a shell of cold, dense fuel. Two criteria have to be met for ignition: firstly, if the hotspot temperature is sufficiently high, fusion reactions occur, emitting alpha particles and neutrons. Secondly, if the hotspot is of sufficient size and density, the alpha particles deposit their energy in the hotspot. This further heats the hotspot causing even more fusion reactions to occur. A thermonuclear burn-wave then spreads into the larger mass of cold, dense fuel, igniting it; ignition. Energy-gain requires that a significant fraction of the fuel must burn up before the imploded fuel disassembles due to its own internal pressure. The fuel’s own inertia briefly confines it, giving rise to the name Inertial Fusion. Note the term inertial fusion is driver independent: it encompasses all driver methodologies.

A key advantage of inertial fusion stems from the small hotspot mass which means a small amount of energy[4] can be used to initiate ignition: improvements in efficiency could potentially result in ignition with relatively small-scale drivers, and hence reduced capital costs. However, in order to create the required conditions for ignition, the pressure requirements are vast, at hundreds of billions of atmospheres. Achieving this pressure over the required confinement time is the key challenge for inertial fusion.

6.1 The International Outlook

Internationally the largest laser fusion research effort is led by the Lawrence Livermore National Laboratory (LLNL) in the USA, using the National Ignition Facility. Based on the Centurion-Halite underground test results, NIF was originally proposed as a 10 MJ facility, but was then deemed too expensive. Instead, 1-dimensional numerical simulations were used to assess the minimum energy with which ignition could be achieved. A minimum ignition energy of ~1.3 MJ was established, and the 1.8 MJ NIF was built. In 2009 the National Ignition Campaign began on NIF, with the goal of achieving fusion energy gain, or ‘ignition’. In August 2021 NIF achieved a record fusion yield of 1.3 MJ using ~ 1.9 MJ of laser energy. This corresponds to an energy-gain (Q) of ~ 0.7 (Q = fusion energy out/laser energy in). While $Q \gg 1$ is required for IFE applications, this result provides clear evidence that the *physics* of Laser Fusion ignition works, as ~ 5.8 times more fusion energy was output than that absorbed by the implosion. A yield of 1 MJ is the commonly accepted scientific definition of ignition. LLNL anticipates further progress on NIF.

NIF uses the ‘indirect drive’ approach to laser fusion; lasers heat a gold cylinder (‘hohlraum’) which then re-emits x-rays, these in-turn drive the implosion. A key advantage of indirect drive is that it smooths the light driving the implosion, this along with other associated physics, reduces the growth of deleterious fluid instabilities which can destroy the implosion. The main

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[4] As little as ~10 kJ of energy is required: about that required to heat a litre of water by 2 °C.

challenge with indirect drive is that only a relatively small fraction of the x-rays generated actually drive the implosion, reducing the efficiency of energy coupling. Thus, while the capsule gain (fusion energy out/capsule absorbed energy) was ~ 5, Q remained below 1. Recent progress suggests that NIF will achieve Q > 1. This would be a huge achievement, however, due to the inherent inefficiency of indirect drive it is our assessment that NIF is unlikely to achieve the energy-gain required for IFE.

A key motivation for the pursuit of the indirect drive approach to Laser Fusion was the poor laser beam quality when this technique was pioneered in the 1970s. Since then, laser technology has improved enormously through the development of smooth far-field beam profiles, spatio-temporal smoothing techniques, and temporal beam-shaping. These developments have opened the door to alternative, far more efficient, and less complex approaches to Laser Fusion which are now being widely pursued.

In laser ‘direct drive’, the laser beams impinge directly on the implosion shell. This has the significant advantage that it is 5-6 times more efficient than via indirect drive; if NIF’s peak performing implosion were driven with the efficiency of direct drive, Q would be at least 3. Moreover, were NIF to employ direct drive, the scale of the implosion would be equivalent to that of a ~10 MJ indirect drive facility; the scale at which NIF was originally proposed. Internationally, direct drive research is led by the US’s Laboratory for Laser Energetics (LLE), using the Omega laser facility. Ignition is not possible on Omega as the laser energy is insufficient, however it is possible to demonstrate the creation of ignition-equivalent implosion performance, albeit at reduced scale: ‘hydrodynamically-equivalent ignition’. Recent progress on Omega has been rapid, achieving an equivalent of ~570 kJ of fusion energy, if scaled to NIF’s energy.

Both NIF and Omega are principally focussed on the central-hotspot approach to laser fusion. A number of advanced laser fusion schemes also exist. According to our theoretical understanding, these inherently produce higher fusion energy-gains. These energy-gains (~200) are suitable for power production and may be possible with a smaller laser than NIF. These advanced approaches include ‘shock-ignition’, ‘electron fast-ignition’ and ‘proton fast-ignition’. All these schemes seek to separate the compression phase from the heating phase and employ the efficient direct drive approach while reducing susceptibility to deleterious hydrodynamic instabilities. These approaches have their own challenges, but many of the physics issues are amenable to study on smaller-scale facilities. Based on their performance on Omega, shock-ignition experiments are predicted to perform very highly when extrapolated to NIF-scale.

Unfortunately, it may not be possible to demonstrate ignition via direct drive methods on existing high-energy laser facilities (NIF/LMJ) as they are designed for indirect drive; without significant reconfiguration (and further investments), this places performance limitations on current direct drive experiments. However, relevant experiments can, and are, performed; in collaboration with LLE, the UK recently proposed and designed the first three shock-ignition experiments on NIF.

Magnetised Liner Inertial Fusion (MAGLIF) is a promising non-laser-based approach to (magneto) inertial fusion. This research is led by the Sandia National Laboratory using the Z Pulsed Power Facility. The main advantage of this approach is a very high electrical to implosion-kinetic-energy conversion-efficiency, meaning that in principle the driver could be of modest scale, and hence cost, in comparison to the equivalent laser.

The US had a very significant Inertial Fusion Energy programme (LIFE) until 2013. A report commissioned by the US National Research Council provides a comprehensive assessment of the prospects for IFE. More details can be found in section 6.11. A recent report by the American Physical Society has called for the re-establishment of a US IFE programme based on recent progress. A meeting to discuss routes forward for Inertial Fusion Energy is being organised by the US for Spring 2022. It is anticipated this may result in the establishment of a substantial US IFE programme. This may bring up a potential opportunity for the UK to be involved as a key partner.

In comparison to the US, European laser fusion funding is relatively modest. This is partly due to the historical association of inertial fusion with defence research. Nevertheless ~0.25% of EUROfusion's €200M annual budget is invested in laser fusion. The UK-led HiPER project (see section 6.8) galvanised significant European laser fusion research and enhanced collaboration. Although HiPER funding has ceased, EUROfusion funding enables ongoing UK-European collaborations, mainly on research into advanced laser fusion concepts.

Within the EU, France has the largest domestic laser fusion research programme; it is principally defence-oriented and uses the indirect drive approach. French academic laser fusion research is mainly focussed on shock-ignition. In Germany, Italy, Spain, Czech Republic, Hungary and Greece a number of academic institutions perform laser fusion research.

European academics have recently developed a plan to re-establish the HiPER project; HiPER-Plus. This project seeks to initially establish a High Energy Density Science research programme focussed on laser fusion physics, broadband laser drivers, and fusion materials. The medium-term goal is to construct an intermediate-scale high energy laser fusion facility in Europe. There is the opportunity for UK researchers and/or institutions to be involved in this collaborative initiative. At this stage HiPER-Plus is unfunded.

China is pursuing both indirect and direct drive inertial fusion with significant investments, although current lasers are sub ignition-scale. Russia's program appears similar to that of NIF or LMJ, although details are scant. Japan's research is performed using the 12 kJ FIREX laser facility and is focussed on electron fast-ignition.

Recommendation

In the context of significant ongoing international investment and large ongoing research-programmes, we recommend that UK-focus should be placed upon two key areas:

- **High fusion-energy-gain laser fusion schemes:** the pursuit of advanced, but scientifically credible, ignition schemes which are not currently prioritised internationally. This will maximise scientific impact, innovation, and the potential for future commercialisation, with the goal of accelerating the path towards Inertial Fusion Energy.
- **The science of ignition:** increasing our understanding of the physics of ignition and the plethora of related high energy density physics; the core scientific foundations for a robust understanding of inertial fusion ignition. This is an area of well-established UK strength and remains a key avenue where the UK innovates, demonstrating global leadership and influence.

6.2 Research Organisation and Funding

UK laser fusion and HEDP funding comes from 3 sources:

- **STFC:** funds the Central Laser Facility (~£5M/yr) but does not fund Inertial Fusion/HEDP research as this does not fall within STFC's remit.
- **EPRSC**: funds responsive-mode research grants in inertial fusion (£600k/yr), HEDP (£4.3M/yr) and post-graduate training.
- **MoD/AWE**: funds defence-related HEDP research and the Orion laser.

The STFC-funded Central Laser Facility (CLF) at the Rutherford Appleton Laboratory, Harwell Oxford is a locus for UK academic laser fusion and HEDP research. It provides a combination of laser facilities, advanced target manufacturing capabilities, computational and simulation code resources, PhD training and hosts the UK XFEL hub. The CLF also funds an annual High-Power Laser conference and supports PhD training.

The majority of UK laser fusion and HEDP research (see section 6.3) is performed at universities, with grant-funding provided by EPSRC with some funding also coming from the US DOE and NNSA.

AWE provides positive input to UK academic research by funding a number of HEDP centres in UK university departments and co-funds some PhD studentships. However, AWE currently has no remit for energy research; this contrasts with the approach taken by the US, France and China. If the UK were to decide to expand laser fusion research in the future, AWE has the potential to bring to bear significant capabilities and expertise.

Given the broad nature of HEDP research, the fact that UK funding comes from multiple bodies (STFC, EPSRC, with AWE/MoD involvement), combined with the need for multiple research facilities, there is the potential for areas of UK research to 'fall through the gaps' between research councils. The UK Inertial Fusion Consortium was created to stimulate collaboration within the UK and provide a collective voice for UK inertial fusion research. A key goal is to facilitate research-community dialogue with funding bodies.

In order to maximise the benefits for all UK stakeholders, the UK Inertial Fusion Consortium will seek to further engage with the broader HEDP community, obtaining their input on community-wide issues such as facilities and training, and communicate these to UKRI.

6.3 Research

High Energy Density Physics encompasses a diverse landscape of research including: High Energy Density Astrophysics, Nuclear Astrophysics, Plasma Astrophysics, Planetary Physics, Plasma Physics, Matter at Extreme Conditions, Warm Dense Matter, Opacity, Radiation Transport, Atomic Kinetics, Equations of State, Laser-Plasma Interactions, Quantum Electro-Dynamics and, of course, Inertial Fusion.

UK laser fusion and HEDP research is consistently world-class, as evidenced by the number of high impact factor publications by UK groups. UK research has significant impact on large international programmes, particularly in the US. It is anticipated that a focussed, collaborative UK inertial fusion effort would significantly expand the impact of UK research and the associated innovation. Academic research institutions include Imperial College London, the University of Oxford, Queens University Belfast, the University of Strathclyde, the University of Warwick, and the University of York.

Ongoing inertial fusion research projects include:

- The development of the EPOCH and Odin simulation codes
- Understanding the options for ignition on NIF
- The application of machine-learning to implosion design
- Research into the shock-ignition approach to laser fusion: including the UK leading the proposal and design of the first three shock-ignition experiments on NIF, UK-led physics and implosion experiments on Omega, and simulation code developments.
- The physics of magnetised inertial fusion implosions
- Kinetic studies of laser plasma interactions for laser fusion
- Low convergence ratio implosions and methods for applying auxiliary heating

UK laser fusion and HEDP funding currently comes from responsive-mode EPSRC grants. However, by its nature, responsive-mode research tends to consist of isolated projects disconnected from an overarching strategy.

Recommendation

We recommend current responsive-mode EPSRC grants should be supplemented by programme-grant funding for laser fusion research through an increase in funding of ≥£2M/annum.

This increase would enable UK researchers to establish a significant programme of laser fusion research, coherently combining the multiple research threads which are vital for progress in laser fusion research: experiments, simulations, the development of new physics models within the simulation codes, code benchmarking, and the associated technologies: laser drivers and targets.

6.4 Innovation, Applications and Technology

The pursuit of laser fusion has been a key driver of laser innovation. Lasers now form the core technology for the global photonics industry. This a growth industry; currently valued at ~$600Bn/annum, it is predicted to exceed $1Tn/annum by 2025. Perhaps surprisingly, photonics contributes more to UK GDP than pharmaceuticals (£13.5 Bn), and employs 69000 people, as detailed in a recent report by the Royal Society. The UK's photonics industry is principally comprised of small and medium enterprises meaning that, unlike pharmaceuticals for example, there is no large single voice within industry to champion its success. While photonics employs lower-power lasers than those required for fusion, this illustrates the commercial rewards that investments in laser technology yield, and the associated potential for future technology spin-outs.

Lasers are ubiquitous throughout the modern world: they provide the backbone of the high-speed internet by sending signals through the fibreoptic networks which connect the world. They also enable laser eye surgery; pioneering research performed at the CLF formed the foundation of this technology. Modern 3D scanning techniques rely on lasers, while driverless cars use the laser-based LIDAR to perceive the surrounding world. High-power lasers are a core technology in high-tech manufacturing; from cutting, drilling and welding, to advanced 3D additive-manufacturing technologies. Lasers form the basis of Quantum Computing, and even enable scientists to see the most distant objects in the universe through the creation of artificial 'guide stars' for modern astronomy. By reading bar-codes, lasers even form the basis of modern complex supply-chains.

UK HEDP research and innovation to-date has resulted in the creation of a number of spin-out companies which include CALTA (ultra-high tech laser manufacturers), Scitech Precision Ltd (micro-scale precision manufacturing), Kentech (specialised electronics and imaging), ANDOR (scientific imaging), Specialised Imaging, Raptor Photonics, and Cobalt Light Systems (airport explosives scanners).

Aside from spin-out companies, there are numerous commercial companies directly investigating novel methods to achieve either IFE or hybrid methods which combine magnetic and inertial fusion methods. These companies include: First Light Fusion (UK), General Fusion (Canada/UK), Hyperjet Fusion Corporation, Helion, Proton Scientific, Magneto Inertial Fusion Technologies Inc., Compact Fusion Systems, LPP Fusion, Horne Technologies, ZAP Energy Inc., Innoven Energy, and Marvel Fusion (Germany). Apart from where indicated, the above companies are US-based, where private fusion funding now exceeds that provided by the government. An important factor that, in the US, has allowed private companies to integrate their efforts with academic partners has been the establishment of ARPA-E grant funding by DOE. A similar programme in the UK would be welcomed.

First Light Fusion is a privately funded company based in Oxford, UK which aims to turn the inertial fusion concept into a commercial power plant using a novel IFE approach. First Light's need to protect their intellectual property means the details of their target designs are not known to the wider Consortium. First Light Fusion replaces the laser driver with a high-velocity projectile, this impacts the target from one side, creating a high pressure, driving the collapse of a fuel capsule within the target. While the First Light Fusion approach is quite different from that of Laser Fusion, there are significant synergies, particularly with respect to fundamental physics and power plant design. First Light Fusion collaborates with the UK research community, details of which are included in the relevant sections of the Roadmap.

While the realisation of Inertial Fusion Energy (see section 6.11) remains a huge challenge, it has the potential to be a truly transformative technology, as evidenced both by the number of companies investigating fusion energy, and longer-term governmental investments. Firstly, there is the potential to ameliorate many of the negative physical, financial and geo-political effects of global warming through the creation of a near carbon-free energy source. Secondly, the principal fuel is found naturally in seawater and is sufficient to power humankind for more than 1 million years. Finally, were the UK to establish itself as a leader in IFE technology, there is massive potential for commercialisation; even if it replaced only a small fraction of the global energy industry, the oil industry alone is worth \$3.2 trillion/annum.

The medium-term technology innovations required to advance UK laser fusion (and HEDP research) fall into two main categories: laser drivers and targets. There is significant expertise in both areas within the CLF. The DiPOLE project (commissioned under HiPER, see section 6.8) has successfully created lasers with sufficient repetition rate and energetic efficiency for energy-generation purposes and has been commercialised by CALTA, generating a range of spin-out applications on the European XFEL, EPAC and ELI.

As detailed in section 6.8., we recommend the further development of the DiPOLE laser technology to $\geq$ 1kJ at 3rd harmonic, with increased bandwidth. A higher energy DiPOLE laser would establish a technological pathway towards Inertial Fusion Energy, potentially enabling the UK to become global leaders in those technologies which are particularly suitable for future power production, thereby maximising the competitive-potential for commercialisation. This would also provide the basis for a future higher-energy UK laser facility (section 6.8).

Scitech Innovations Ltd, another spin-out of the CLF, has extensive target manufacturing capabilities and expertise. IFE requires ~1 million implosion targets per day per reactor, which, were IFE realised, presents enormous commercial opportunity. However, at present there is no UK implosion target manufacturing capability. As a consequence, implosion targets currently have to be bought from the US.

Recommendation
In order to develop strategic skills, knowledge and build upon cutting-edge UK technological and manufacturing capabilities, we recommend the CLF develops an implosion target manufacturing capability. With IFE and commercial advantage in mind, novel technologies for the low-cost, mass-manufacture of implosion capsules should also be pursued.

Outside of laser fusion, many historical HEDP applications have been in the defence sector. These include guidance systems and ship-defence lasers. However, this picture is rapidly evolving as evidenced by the recently funded £81M Extreme Photonics Applications Centre (EPAC) at the CLF. EPAC will use HEDP to create an array of particle and light sources for a wide range of innovative applications. Laser-driven, plasma-based particle accelerators are advancing rapidly, with the goal of creating the technological basis for a range of future technologies, from next-generation particle-accelerators and light-sources, to ion-beam cancer therapy.

Perhaps the most striking example of the current application of HEDP technology is in the fabrication **all the most-advanced microchips**, such as those in the latest iPhone. This ~$60 Bn/annum growth industry has been enabled by the extreme conditions accessed via HEDP, which are otherwise inaccessible in the laboratory. These now from the basis of this cutting-edge photolithography process. The application of High Energy Density Physics creates 13 nm wavelength extreme-ultraviolet light, in turn enabling the creation of cutting-edge 5 nm feature-size microchips via photolithography. The international patent for this is held by a CLF researcher. The development of this cutting-edge multi-billion-dollar industry illustrates the transformative innovations which targeted investments in HEDP can realise due to their unique ability to access extreme conditions within the laboratory.

6.5 Training

As detailed in section 6.3, UK PhD training in HEDP and Laser Fusion is provided by Imperial College London, the University of Oxford, Queens University Belfast, the University of Strathclyde, the University of Warwick, and the University of York. The CLF also provides training through access to its facilities, training courses, and PhD support. AWE and First Light Fusion also sponsor PhDs.

UK laser fusion and HEDP trained researchers are extremely highly regarded internationally, as evidenced by the high number of UK-trained researchers holding senior positions at US national labs. Post-graduate students trained in laser fusion and HEDP also form an important component of the UK workforce. They are highly trained in areas such as complex decision making, problem solving, advanced engineering, programming, artificial intelligence, mathematics, statistics etc, and often work in international teams; post-graduate students contribute extensively to the wider knowledge-economy.

A significant issue in recent years has arisen from EPSRC’s shift towards Centres for Doctoral Training (CDT). Currently there is only one UK CDT related to Laser Fusion/HEDP and even this was only funded in the most recent round after intervention by BEIS. This situation has resulted in a considerable drop in the number of PhD students in HEDP related subjects over recent years. This poses a real threat to the UK’s international standing in HEDP, Laser Fusion research, our ability to run large-scale facilities, and support defence-related activities.

Recommendation
In order to provide a PhD trained workforce in numbers commensurate with the UK’s broader investments in research, facilities and defence, we recommend a UK-wide training scheme for HEDP should be established by the relevant UK research institutions and integrated with UK facilities.

Currently UK laser fusion and HEDP suffers from significant ‘brain-drain’, particularly to the US. This is principally caused by the lack of post-doctoral, and in particular permanent positions at UK institutions. Establishing a UK programme of laser fusion research may be of considerable benefit in slowing the UK-to-US brain-drain, as it would provide additional post-doctoral positions and the prospect of working in an inspiring research area. First Light Fusion has become a significant employer of HEDP trained researchers in the UK, with a core science and engineering team of ~40.

6.6 UK Facilities

The principle UK inertial fusion/HEDP research lasers are Vulcan (Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Oxford) and Orion (AWE, Aldermaston).

Orion is a 6 kJ laser based on the indirect drive concept. Orion fields ~1 experiment per year for ‘open’ academic research which, while benefitting the research community, severely limits its applicability to a programme of ongoing laser fusion research.

Vulcan is openly available for research and is a world-class facility for high-intensity research. Through a number of upgrades, Vulcan has been the UK’s workhorse for academic HEDP and laser fusion research for ~30 years. A short-pulse beam (OPPeL) is currently being added to Vulcan which will enable the creation of ‘betatron’ x-rays to probe Vulcan laser-plasma interactions and is an excellent development. Currently Vulcan faces two principal challenges: firstly, its age limits reliability, secondly the available high-energy (‘long-pulse’) beams limit the range of inertial fusion/HEDP experiments which can be performed. These can be addressed through investment.

By funding the proposed ‘Vulcan 2020’ upgrade, this will place Vulcan at the forefront of high-intensity research while significantly improving the scope of ‘long-pulse’ laser-fusion/HEDP research which can be performed. This would enable a broad-range of experiments which would stimulate innovation and underpin our understanding of the complex, coupled physics of inertial fusion through the rigorous testing of physics packages within multi-physics simulation codes. Furthermore, it would provide an ideal platform for the development of new diagnostic techniques whilst training the next generation of scientists and engineers. **We strongly support the Vulcan 2020 proposal as detailed in a recent letter of support from the wider UK community**. Beyond this, the UK Inertial Fusion Consortium encourages close design consultation with the UK research community in order to maximise the benefits of any investment for laser-fusion/HEDP research.

Recommendation

- **Vulcan (near-term):** We recommend ongoing investments in Vulcan with a particular focus on improving reliability, long-pulse beamline characteristics (third harmonic radiation and further develop beam pulse-shaping and smoothing capabilities) and diagnostic provision.
- **Vulcan (medium-term):** We recommend the proposed Vulcan 2020 upgrade is funded. This will extend the usefulness of Vulcan long and short pulse capabilities for laser fusion research, stimulate innovation, and enable the gathering of large data sets relevant to standard and advanced laser fusion concepts such as fast and shock ignition.

The recently announced £82M Extreme Photonics Applications Centre (EPAC) is a welcome investment which will greatly benefit areas of HEDP and related applications. As well as enabling the development of a diverse range of novel HEDP applications, this facility will provide an excellent platform to develop our understanding of laser-target operations at the high laser-pulse repetition rates which are critical for future Inertial Fusion Energy applications. Furthermore, it will be ideal for stimulating innovation, the testing of novel diagnostic techniques, and further increasing the UK skills and research base. It is important to highlight that while EPAC is an excellent development, due to its modest laser energy (~150 J) the range of inertial fusion research which can be performed is limited, thus Vulcan 2020 and the further development of DiPOLE to higher energy must be pursued. Finally, investment in EPAC further highlights the need for UK post-graduate training in HEDP.

A number of smaller UK university-based facilities also exist, these include the Cerberus and Chimera lasers, and MAGPIE ‘z-pinch’ at Imperial College London, the Taranis laser at Queens University Belfast, three lasers at the University of Oxford (10 J / 20 ns, 50 mJ / 50 fs and 600 mJ / 45 fs / 1 Hz), the SCAPA centre at the University of Strathclyde and a short wavelength (46.9 nm) 0.1 mJ / 5 ns / 10 Hz laser at the University of York.

First Light Fusion has four main experimental platforms, two two-stage gas guns and two pulsed power machines, the larger of which is the second highest current pulsed power machine globally. Access to its experimental facilities has been offered to the academic community.

6.7 Access to International Laser Facilities

To-date UK academia has principally accessed international facilities via open-calls for proposals, or through collaborative research. These approaches have been highly successful in creating high-impact UK HEDP research publications; however, we assert they are not a suitable basis for an ongoing programme of laser fusion research. This is for two reasons: firstly, open-calls on international facilities often specifically exclude laser fusion research, secondly, and perhaps most importantly, in order to answer the open questions for laser fusion, a strategic, at times incremental, approach to research is necessary. This is simply not possible if access is only obtained through open-calls or non-UK-led collaborations on experiments.

Recently a new access route to international facilities for UK researchers has been established: purchasing experimental time on the Omega laser facility. This has proven an extremely effective route to performing laser fusion research and has resulted in significant financial leverage: the cost of the Omega experiments to date has been ~£300k, but these have enabled UK participation in experiments on Omega and NIF with total value of ~£4M and access to datasets worth ~£25M. Importantly, near-term investment in purchased experimental time on the Omega laser facility would enable the UK to establish a significant laser fusion programme of research with minimal costs. It is important to note that Omega is one of only three facilities internationally (the others are NIF and JET) which can perform DT fusion experiments.

Recommendation
In the context of grant funded research, we recommend UKRI/EPSRC continue to invest in Omega laser facility experiments for laser fusion and HEDP research.

A novel facility-access mechanism which should be evaluated is establishing a joint UK-US call for facility access. This might be facilitated by a joint UKRI/DOE research agreement (see section 6.9). This would enhance UK-US collaboration and, given the high investment levels in the US, has the potential to generate significant financial-leverage for the UK.

6.8 Future Facilities

From 2008-13 the Central Laser Facility led an STFC-funded pan-European project aimed at the demonstration of high-gain laser fusion: HiPER. This project demonstrated significant UK leadership in the field and galvanised pan-European research collaborations. While this proposed facility was added to the ESFRI Roadmap, it has not been funded to-date as it was predicated on the demonstration of ignition on NIF. Currently a European consortium is seeking to re-start the HiPER project, it is currently unclear what role the UK will play in this.

A key outcome of the HiPER project was the development of the world-leading and commercially successful DiPOLE laser concept (also see section 6.4). This enables the creation of laser pulses with the energy efficiency and pulse repetition rates required for Inertial Fusion Energy applications. The initial development does not however have sufficient energy for IFE applications, consequently we recommend the further development of the DiPOLE laser technology to ≥ 1kJ at 3rd harmonic, with increased bandwidth.

Recommendation
We recommend the CLF further develops DiPOLE technology by increasing the energy to the ≥1 kJ level at 3rd harmonic with increased bandwidth.

An improved DiPOLE laser system would provide multi-fold benefits to UK research: firstly, based on DiPOLE's success to-date (EU XFEL, EPAC, HiLASE), this will likely result in a wide range of future applications outside the UK, with the associated commercial potential. Secondly, this will establish a technological pathway towards Inertial Fusion Energy; the construction of a single prototype beamline is a key step in de-risking any future multi-beamline high-energy laser-compression facility. Were such a prototype to be constructed in the new EPAC building for example, this could provide the basis for a new laser facility which would significantly enhance both the UK's HEDP research and high-intensity research capabilities: by applying Chirped Pulse Amplification (see the 2018 Nobel Prize), the high-energy beam could be compressed in space and time, creating a world-class, and potentially world-leading, high-intensity, high repetition-rate laser. Furthermore, the 'long-pulse' characteristics would enable the gathering of large, statistically averaged datasets on the key physics underlying HEDP and laser fusion, a feat that is simply not possible on today's low-repetition rate facilities (e.g., NIF fires a maximum of 4 times per day).

It is now deemed highly likely that NIF will demonstrate fusion energy-gain greater than unity. However, it almost certainly won't create sufficient energy-gain for IFE - it was not designed to do so. Consequently, for the demonstration of the viability of Inertial Fusion Energy, a new Laser Fusion facility will be required. Given the cost of such a facility is likely to be high, there may be an opportunity for the establishment of an international approach to Inertial Fusion Energy. This presents a significant opportunity to the UK to be a key partner either in a UK-US collaboration, or potentially, in a wider international collaboration.

Recommendation
We recommend undertaking a detailed evaluation of the benefits of, and potential funding-routes for, a new Laser Fusion facility to demonstrate sufficient energy-gain for Inertial Fusion Energy. Possible avenues might include the creation of an international facility or under a bi-lateral agreement between the UK and US.

The science case for a UK XFEL has recently been published. The coupling of a laser-driven spherical-compression facility to an XFEL with sufficiently high x-ray energy would enable the diagnosis of extreme states of matter in unprecedented detail, leading to significant advances in laser fusion and HEDP. *This would be a transformative marriage of technologies which would be globally unique*, enabling the UK to attain a leadership position in the associated science and technologies. Depending on its energy-scale, a laser-compression facility could add significant cost to a UK XFEL. As discussed above, one option which should be explored, is the possibility of establishing an international Laser Fusion facility.

Recommendation
We recommend undertaking a detailed evaluation of the benefits of, and funding-routes for, the co-location of a laser-driven spherical-compression facility with, for example, the UK XFEL, if constructed.

6.9 Collaborations

The UK academic sector (including the CLF) contains a diverse range of world-class skills, experience, knowledge, and simulation codes, which cover the full range required for a UK programme of laser fusion research. Through collaboration, with the appropriate funding, and a diligent choice of research-focus, the UK academic sector has the potential to be world-leading in aspects of laser fusion research which are not prioritised internationally. This is evidenced by historic UK world-leading efforts in a number of related research areas and its consistent excellence in publishing high-impact research. The UK Inertial Fusion Consortium has been established specifically to foster collaboration and coordination within the UK. *It is our assessment that the most appropriate method to enhance inter-UK collaborations in laser fusion research would be though programme-grant funding and, in the near term, investment in Vulcan. This would leverage the significant existing UK technological and research skills-base.*

AWE has the potential to bring to bear significant capabilities to UK collaborations, however, the extent to which it is able to collaborate with UK academia is limited to those areas of broad interest to its own scientific programmes. A wider remit for AWE to perform energy-specific research would likely require funding from outside the MoD and agreement with the MoD on the use of its capability investments. This could have a significant positive impact on the scope and scale of UK laser fusion and HEDP research.

There are opportunities for further collaboration with First Light Fusion. Areas include fundamental physics; numerical methods; experiments on First Light Fusion's facilities; the design of future facilities; and the engineering challenges of an inertial fusion power plant.

There are a number of synergies between Inertial Fusion and Magnetic Fusion. These include materials science, non-local heat transport and many aspects of power-plant design, such as tritium-breeding. A number of collaborations between UK inertial fusion researchers and the Culham Centre for Fusion Energy are ongoing. Avenues for enhanced collaboration will be pursued by the Consortium.

Globally, the US leads laser fusion and HEDP research. The AWE has deep historical connections with the US which enables their access to the NIF and Omega laser systems. Furthermore, UK academics perform open collaborative research with US labs and universities, in particular LLNL, LLE and Sandia.

Recommendation

We recommend the existing strong UK-US research relationships are built upon by UKRI/BEIS establishing formal UK-US research agreements, potentially with a specifc focus on Inertial Fusion Energy. For example, a joint agreement between UKRI and DOE and/or NNSA would be highly beneficial to both parties by encouraging the exchange of diverse scientific ideas. This approach may enable the UK to leverage significant ongoing US investments in facilities.

UK-European collaborations are extensive and have been funded by the HiPER project, EUROfusion, Horizon 2020 and Laserlab Europe. These are an important component of UK research collaborations. The proposed re-establishment of the HiPER project (by European researchers) is an opportunity for UK researchers to increase collaborations within Europe.

More broadly, UK researchers also collaborate with a range of international research institutions, in particular in Japan, and increasingly with China, which is a rising power in HEDP and Inertial Fusion research.

International collaborations in Inertial Fusion are an important aspect of current research. However, to-date they have typically been limited to two-party agreements. This is at least in part due to the close proximity of Inertial Fusion to defence research and the associated sensitivities. If it were possible to develop collaborations, perhaps with a focus on IFE, with a broader multi-lateral international scope, this would be highly beneficial to the future prospects of IFE. We will endeavour to develop such collaborations in the medium-term.

6.10 Simulation Codes

UK academia has two main radiation-hydrodynamics simulation codes Gorgon/Chimera (3D Eulerian) and Odin (2D Arbitrary Lagrangian Eulerian). Access to the 3D Eulerian with Adaptive Mesh Refinement MHD radiation-hydrodynamic code FLASH is also available to the UK community. These are complemented by a number of approaches more suited to investigating specific areas of physics: EPOCH (3D particle-in-cell), Kalos, CTC (2D transport), Zephyros (3D hybrid electron-transport) and the commercial Prism codes (experimental design, atomic physics, equation of state, synthetic diagnostics).

Radiation-hydrodynamics simulations form a critical foundation for all inertial fusion and HEDP research. However, experience on NIF tells us that while their ability to predict experimental behaviour is very good, they are not (yet) sufficiently predictive to design an indirect drive ignition implosion. Although it is not yet possible to test this at ignition scale, this may be true for direct drive too. It is our opinion that, in order to make further progress, ongoing code development is required which emphasises the development of new physics models within existing codes, crucially these must then be tested against experiments. Due to its longer-term, incremental nature, simulation code development is not well-matched with responsive-mode grant funding, however it is critical for UK research.

Recommendation

We recommend an appropriate long-term funding-route for UK simulation-code development is established which reflects their evolved-status into critical research infrastructure.

The capabilities and control of access to such codes would need to be consistent with government guidance and the UK’s undertakings with respect to nuclear non-proliferation.

6.11 Inertial Fusion Energy

The fuel cycle for fusion involves extracting deuterium and lithium from sea water. Tritium is then ‘bred’ within the reactor from lithium. 1 litre of seawater could generate roughly 1 kWh of fusion power, meaning fusion can provide enough energy to power the world for millions of years. While this represents a huge technological challenge, it is clear that if a power production technology with sea water as the principal component could be made economically viable, there would be the potential for huge economic gains for the UK.

As a potential power source, our view is that laser fusion has huge potential, but, like all fusion schemes, faces significant technical challenges. Although a significant number of technical challenges are unique to a given fusion-approach, many challenges are shared between both magnetic and inertial fusion, as detailed in a recent paper. These shared challenges include tritium handling and the tritium cycle; materials and their survivability in the high-energy neutron environment of D-T fusion; neutronics and the validation of nuclear data; remote handling and maintenance activities; and integrated holistic approaches to fusion plant design. These highlight areas where knowledge-sharing and collaboration could be particularly beneficial between the inertial and magnetic fusion communities.

A significant number of projects have performed detailed design studies of how a laser fusion power plant might work in practice (e.g. HiPER and LIFE), while commercial fusion companies are actively investigating IFE reactor concepts.

In comparison to other fusion approaches Inertial Fusion Energy offers a number of potential technological advantages, as detailed in a comprehensive recent US National Academies of Science Engineering and Medicine report by the National Research Council. These are briefly discussed below.

A key potential advantage of the Inertial Fusion approach is the physical separation of the hot plasma from the surrounding infrastructure. For example, in laser fusion, the lasers can be focussed onto the target from a significant distance. This physical separation will reduce neutron and thermal damage to the surrounding infrastructure, potentially ameliorating significant technological risks associated with other fusion approaches.

Tritium is one of the two fuels required for fusion. Globally its supply is currently extremely limited. Research indicates that IFE power-plants have the potential to dramatically reduce the required Tritium inventory over other approaches.

IFE technology is inherently modular as the target physics is essentially decoupled from both the driver and power-plant technologies. This is advantageous as it enables progress to be made in parallel on all fronts: drivers, targets and physics. This decoupling also means that one scientific facility can be used to investigate numerous physics approaches to IFE in parallel.

Technological challenges unique to IFE include: the economical mass manufacture of targets; issues regarding the potential damage of final optics (in the case of Laser Fusion); the pulsed nature of any neutron and fast-ion damage; and target injection, tracking, and survivability in the reaction chamber.

The National Academies report advocates promoting industry awareness of the complexity of the technology (a perceived barrier) and of the availability of complementary resources (a perceived advantage) for technology commercialisation by small and medium enterprises (SME). SME interest in forming bid consortia for a demonstration IFE fusion power plant and establishing the requisite supply chains would provide valuable leverage in realising IFE.

The indirect drive approach may well provide the initial demonstration of ignition; however, due to its inherent inefficiency in coupling laser energy to the implosion, it may not have sufficient fusion-energy-gain for practical power production. Furthermore, the hohlraum materials will cause the production of long-lived radioactive nuclides. Consequently, it is probable that either direct drive or a high-gain advanced scheme, as described in Section 8.1, will be required for power production purposes. This view was largely echoed during a Hooke discussion meeting on the "Prospects for High Gain Inertial Fusion Energy" at the Royal Society in London in March 2020, during which eighty international delegates met to discuss the state of the art and to discuss prospects for high fusion-energy-gain.

With reference to the aforementioned National Academies report, the principle limiting factors in the economics of Inertial Fusion Energy are likely to be the cost of targets and, due to the potentially high capital cost, the facility availability (limited by maintenance down-time). These characteristics imply that inertial fusion schemes which employ simple targets (that are amenable to economic mass-manufacturing) and have the potential for high fusion-energy-gain with relatively small driver energy-scale (thereby minimising capital cost), should be prioritised. In the specific context of laser fusion, these characteristics appear most compatible with advanced direct drive designs such as shock ignition, due to the simplicity and drive-efficiency afforded by excluding the hohlraum, and the potential for high-gain. *We assert that the UK can best place itself to maximise scientific impact and take advantage of future economic benefits of inertial fusion energy by becoming global leaders in those areas of inertial fusion which have the potential for high fusion-energy-gain with low driver energy, and hence are most suitable for application to future power production.*

All ignition-scale lasers to-date have been designed for indirect drive, which makes direct drive approaches challenging on these facilities. Therefore, demonstration of sufficient fusion energy gain for power production may require the construction of a new laser fusion facility. Whilst we do not advocate the immediate construction of such a facility, given the proximity to ignition of the indirect drive scheme and direct drive ‘hydrodynamically-equivalent ignition’, *we see a near-term opportunity for the UK to become global leaders in those areas of science and technology which are particularly suitable for future power production* (i.e., have high theoretical fusion-energy-gain). In this context, there may be opportunities for the development of smaller-scale high repetition rate facilities, particularly for technology development and innovation. This has potential to enhance UK innovation and competitiveness in what may become a significant global market. These areas are not being prioritised by the two ignition-scale international facilities (NIF and LMJ).

We deem there to be three near-term scenarios which would have a significant impact on the viability of laser fusion for future power production: firstly, the demonstration of energy-gain on NIF, secondly the demonstration of ‘hydrodynamically-equivalent ignition’ on Omega, and finally a US decision to pursue the development of Inertial Fusion Energy.

Recommendation

We recommend the UK undertake a review of inertial fusion in the context of fusion energy in order to establish a UK strategy. This should be performed in 2025, unless ignition or hydrodynamically-equivalent ignition is demonstrated, or the US position on Inertial Fusion Energy changes dramatically, in which case the review should be brought forward.

An analysis of the economic viability of inertial fusion as a power source is beyond the scope of this report, instead we point out a few key facts. Firstly, humankind needs a replacement for the carbon-intensive energy supplied by the $3.2 trillion/annum oil industry. While renewables (solar, wind etc) can provide a significant fraction of this power (~ 60%), it is deemed unlikely they can provide a complete solution for humankind’s carbon-free energy needs. This is due to a combination of renewables’ capacity-potential, combined with the intermittency of supply. Nuclear fission offers an attractive near-term solution to zero-carbon baseload electricity, however it has two principal disadvantages: the potential for nuclear accidents such as ‘melt-down’, and the production of long-lived radioactive nuclides, which must be safely stored for approximately 100,000 years. Due to its inherently safe nature, essentially infinite supply, and the fact that no long-lived radioactive waste need be produced, fusion has the ideal characteristics to provide long-term clean power for humankind.

7 The UK Inertial Fusion Roadmap

This Roadmap sets out the UK community's agreed vision for transforming UK laser fusion research over the coming decade. Through a series of ambitious but achievable goals we aim to establish the UK as a world-leader in the key aspects of high fusion-energy-gain research. This maximises relevance to future power production, and hence is most applicable to future commercialisation. The goal of this Roadmap is not to provide a detailed technical description – this will be set out in future grant applications – instead it provides a broad overview of the community's agreed vision.

The plan begins by emphasising increased collaboration and coordination of the UK's existing Inertial Fusion and HEDP research-base, increasing the numbers of post-graduate students, and enhancing collaborations with UK IFE industry. Medium term (~5 year) goals focus on answering key scientific questions relating to ignition, and the development of key enabling technologies: future laser architectures, targets, diagnostic-techniques and simulation-codes. This approach will ensure the UK is best placed to capitalise on the huge potential for commercial gains from inertial fusion power production.

The longer term (~10 year) goals are highly dependent on near-term progress and are subject to the findings of the UK Inertial Fusion Review, nevertheless they provide a focus for near-term activities. They are focussed on the pursuit of Inertial Fusion Energy, both in terms of establishing the most appropriate technologies and whether this should be pursued as a UK endeavour or as a key player within a larger international collaboration.

2021

- Submission of an innovative, coordinated and collaborative inertial fusion-focussed programme grant with broad community support and integration.
- Establishing Odin as a community-accessible simulation code.
- Supporting and promoting the Vulcan 2020 application as a leading international facility for the pursuit of cutting-edge HEDP research and applications development.

2021-25

- Research:
    - Evaluation of the key physics issues facing high-gain inertial fusion
    - The development of new 'reduced' physics models and their incorporation into hydrodynamics simulation codes (see below)
    - Testing key physics in dedicated experiments on smaller facilities
    - Using machine learning to identify and optimise new implosion designs
    - The creation of a robust high-gain laser inertial fusion ignition design
    - Utilise EPAC as a high repetition-rate facility for gathering statistically significant datasets that will enable uncertainty quantification of key physics and the understanding of large facility operations at IFE power-plant repetition-rates.

- Simulation code capabilities:
    - Establish multi-dimensional, benchmarked, predictive simulation capability/capabilities based on:
        - Multi-scale experiments
        - The development and integration of new theoretical models
        - The identification of gaps in current understanding
        - Extensive benchmarking against experiments

  - The development of a comprehensive suite of synthetic diagnostics and analysis routines made freely available to the UK research community
  - Obtaining access to computing resources sufficient for extensive 3D computation

- Technology:
  - Support Vulcan 2020 developments and emphasise its significant potential to support UK laser fusion research and innovation that spans standard and advanced inertial fusion concepts and the development of new laser and plasma diagnostics.
  - The design of a single prototype laser beamline (based on DiPOLE technology and experience using the high repetition rate EPAC) with characteristics appropriate for multi-fold replication for a future laser fusion facility.
  - The development of a UK implosion-target manufacturing capability.
  - Enhance the UK competitiveness-potential by building knowledge and understanding of high repetition rate facilities and operations through EPAC, DiPOLE and the associated target manufacture technologies.
  - IFE power plant: high-level identification of key risks and mitigation strategies.

- Training:
  - The creation of a UK-wide HEDP training scheme which will be integrated with existing training networks, the CLF's High-Power Laser meeting, the CLF's training weeks, and dedicated code training workshops.
  - Increasing the number and diversity of early career researchers (ECR) engaged in inertial fusion/HEDP research.
  - Involving ECRs in strategic research developments through their engagement in the UK Inertial Fusion Consortium.

2025

- UK Inertial Fusion Review: by providing scenarios for different levels of UK ambition, this review should enable an appropriate longer-term UK strategy for Inertial Fusion Energy to be established. The review should:
  - Review prospects for different physics designs/approaches
  - The prospects for future power generation via inertial fusion, including economics
  - Provide options for differing levels of UK ambition: e.g. a dedicated UK capability, or a key partner within an international collaboration.
  - Evaluation of the most appropriate route to achieving high-gain, selecting from:
    - A new facility, possibly as an 'end-station' of a UK free-electron laser
    - A significant upgrade to Vulcan or Orion.
    - An international direct drive facility
    - Other technologies
  - Identify mechanisms, structures and stakeholders for UK IFE programme leadership

----------------- Subject to the outcomes of the UK Inertial Fusion Review -----------------

2025-2028

- Construction and commissioning of a single laser fusion beamline
- The design of a new inertial fusion facility with a pre-defined upgrade path for Inertial Fusion Energy, principally through an increase in shot rate

2028-35

- The construction and commissioning of a testbed inertial fusion facility

2035 onwards

- Develop a robust understanding of the physics, engineering and commercial basis for electrical energy production via inertial fusion

- Upgrade the facility shot repetition-rate to that of a demonstration Inertial Fusion Energy facility

8 Acronyms

ARPA-E	Advanced Research Projects Agency-Energy. A US funding agency.
AWE	The UK Atomic Weapons Establishment, Aldermaston.
BEIS	UK governmental Department of Business Energy and Industrial Strategy
CALTA	Centre for Advanced Laser Technology and Applications, based in the CLF.
CDT	Centre for Doctoral Training (EPSRC funded PhD training centre).
CLF	The Central Laser Facility, Rutherford Appleton Laboratory, Harwell Oxford.
DiPOLE	A CLF-developed high energy-efficiency Diode Pumped Solid State Laser.
DOE	The United States' Department of Energy.
ELI	Extreme Light Infrastructure: A pan-European laser research infrastructure.
EPAC	The CLF's Extreme Photonics Applications Centre, under construction.
EPSRC	Engineering and Physical Sciences Research Council, a UKRI funding body.
ESFRI	European Strategy Forum on Research Infrastructures.
EU	European Union
GLC	Generalised Lawson Criterion, a measure of the proximity to robust ignition.
HEDP	High Energy Density Physics
HiPER	A proposed, but to-date unbuilt, European laser inertial fusion facility.
ICF	Inertial Confinement Fusion
IFE	Inertial Fusion Energy: energy production via inertial fusion.
ITER	International Thermonuclear Experimental Reactor, under construction.
JET	Joint European Taurus, Culham, UK.
LIFE	Laser Inertial Fusion Energy: An IFE project at LLNL.
LLE	Laboratory for Laser Energetics, University of Rochester, NY, USA.
LLNL	Lawrence Livermore National Laboratory, Livermore, CA, USA.
LMJ	Laser Mega Joule, Bordeaux, France.
MAST	Mega Ampere Spherical Tokamak, Culham, UK.
MCF	Magnetic Confinement Fusion.
MoD	The UK's Ministry of Defence
NIF	National Ignition Facility, LLNL.
NNSA	The United States' National Nuclear Security Administration (DOE)
Orion	The AWE's laser system.
STFC	The Science and Technology Facilities Council, a UKRI funding body.
UKRI	United Kingdom Research and Innovation
Vulcan	The CLF's highest-energy laser system.
XFEL	X-ray Free Electron Laser

9 Roadmap Signatories

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10 The UK Inertial Fusion Consortium

The UK Inertial Fusion Consortium has been established to foster collaboration, coordination and establish a collective voice within UK research. It is comprised of ~90 members from:

- Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Oxford, UK.
- Plasma Physics, Department of Physics, Blackett Laboratory, Imperial College, London, UK.
- Centre for Fusion, Space and Astrophysics, Department of Physics, University of Warwick, UK.
- Department of Physics, University of Oxford, Parks Road, Oxford, UK.
- AWE Aldermaston, Reading, Berkshire, UK.
- York Plasma Institute, Department of Physics, University of York, Heslington, York, UK.
- Department of Physics, University of Strathclyde, Glasgow, UK.
- Queen’s University Belfast, Belfast, UK.
- University of Lancaster, Lancaster, UK.
- First Light Fusion, Oxford, UK.

The Chair is Dr Robbie Scott (email Robbie.scott@stfc.ac.uk). More information, including members’ details can be found on our website.