A high energy pulsed power facility – implications for UK research and development

Conference report

THE
ROYAL
SOCIETY

Cover image
© iStock/pixelparticle

Contents

Introduction

Fusion energy has the theoretical potential to provide near limitless energy with minimal pollution. For decades it has been described as 30 years away, yet recent years have seen notable development in research owing to stable public investment since the 1950s, increasing private investment over the last 20 years, and the development of enabling technologies. While progress has been significant, it remains unlikely that fusion will play a key role in world energy production before 2050 without a considerable breakthrough.

Area of action

Leaders in energy innovation policy in the Department for Energy Security and Net Zero should ensure that funding decisions for fusion technologies actively incorporate input from experts with knowledge of – but not limited to – energy infrastructure, science and technology innovation, defence, key skills pipelines (particularly engineering skills such as high voltage engineering and pulsed power engineering), and agglomeration effects, as well as scientific research funding councils responsible for a number of specific basic and applied research areas (see below) and relevant academia.

The science of fusion

Fusion energy is a form of power generation from nuclear fusion reactions. When two light atoms are forced to collide under intense heat and pressure, they form a heavier atom and energy is released. Fusion energy uses isotopes of hydrogen and creates no carbon emissions and minimal nuclear waste (from small scale activation of the surrounding vessel). This process differs from fission nuclear energy, where a neutron collides with a larger atom, forcing it to split into two smaller atoms and producing further neutrons. Energy is released when the atoms split. Fission energy creates nuclear waste, and the large atom used – often uranium-235 – is only found in tiny concentrations naturally.

Whilst fission energy production has been commonplace since the 1950s, the future of fusion energy remains uncertain because the conditions needed to create a fusion reaction are difficult to sustain for long periods of time due to the very high pressures and temperatures needed. Despite this, the enormous potential benefits of clean, sustainable fusion energy have driven consistent government investment in research over many decades.

Investment in fusion

Since the 1950s, the UK government has consistently invested in fusion energy[1]. Historically, the high risk in fusion experiments meant that investment in fusion research came predominantly from the public sector. This balance has shifted in the last 20 years; private investment in fusion technologies has increased as research has progressed, with the value of private investments nearly tripling from $1.5billion between 2016-2020 to $4.44billion in 2021[2]. This investment has led to progress in several technical areas, including the creation of high temperature superconducting magnets for fusion using a ‘tokamak’ device (using magnetic fields to confine hydrogen gases heated to very high temperatures), and achieving fusion ignition (the point at which the fusion reaction creates more energy than was delivered to the target)[3] [4] [5].

---

[1] Department for Business, Energy & Industrial Strategy. 2020 The impact of the UK’s public investments in UKAEA fusion research Final report. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/937633/impact-uk-investment-fusion-research.pdf (accessed 31 May 2023).

[2] McKinsey. 2022 Will fusion energy help decarbonize the power system? See https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/will-fusion-energy-help-decarbonize-the-power-system (accessed 31 May 2023).

[3] White S. 2023 World-first “super” magnets built by Tokamak Energy for fusion power plant testing. Tokamak Energy. 6 February 2023. See https://www.tokamakenergy.co.uk/2023/02/06/world-first-super-magnets-built-by-tokamak-energy-for-fusion-power-plant-testing (accessed 31 May 2023).

[4] Kleinman M. 2023 Fusion energy pioneer Tokamak hires JP Morgan for huge fundraising. Sky News. 12 January 2023. See: https://news.sky.com/story/fusion-energy-pioneer-tokamak-hires-jp-morgan-for-huge-fundraising-12785297 (accessed 31 May 2023).

[5] Bishop B. 2022 Lawrence Livermore National Laboratory achieves fusion ignition. Lawrence Livermore National Laboratory. 14 December 2022. See https://www.llnl.gov/news/lawrence-livermore-national-laboratory-achieves-fusion-ignition (accessed 31 May 2023).

These successful fusion experiments are significant steps in advancing the potential for fusion as a future energy source. With investment in fusion technologies significantly increasing, and other countries advancing their national fusion facilities[6], it is timely for the UK Government to consider how best to position itself internationally regarding the UK's existing comparative and strategic advantage in fusion technologies and skills.

Given the high degree of uncertainty in the viability of practical fusion power, but the extraordinary possible global impact if realised, public policy has been generally predicated on a 'high risk/high reward' basis. This has placed a particular emphasis on defraying investment risk by maximising the investment co-benefits, such as scientific advances with wider applicability, spinouts, and highly skilled, adaptable people. In the UK such co-benefits have included:

- The Materials Research Facility (MRF), which enables industrial and academic researchers to analyse the effects of irradiation on materials.
- The Remote Applications in Challenging Environments centre (RACE) programme, which conducts research and commercial activities in Robotics and Autonomous Systems (RAS) for fusion and adjacent fields including driverless vehicles, intelligent mobility, smart infrastructure, augmented reality, and robotics in hostile environments.
- Oxfordshire Advanced Skills (OAS), which provides training facilities and apprenticeships in the high value manufacturing sector.
- H3AT, which provides research into tritium breeding, processing, distribution, storage, recycling and disposal for academia and industry.

The long cycle of UK investment in fusion has created an ecosystem with many scientific and economic benefits to the UK. Examples of these benefits include:

- 1,312 research papers have been published between 2017-2021 from fusion research[7].
- The UKAEA (Atomic Energy Authority) hosts the Joint European Torus (JET), which is the world's most advanced tokamak, and is used by over 350 scientists and engineers from more than 40 European laboratories[8].
- JET experiments and UK financial contributions have been fundamental in creating the design and construction of ITER, which will become the world's largest tokamak device.
- The UKAEA is also planning STEP (Spherical Tokamak for Energy Production), with the aim to deliver a prototype fusion energy plant by 2040.

Overall, government analysis indicates that UKAEA's activities have had an estimated total economic value to the UK economy of £1.4billion between 2009 – 2019 — a return of approximately £4 for every £1 of investment — and have supported a total of 29,116 job years[9] [10].

---

6 World Nuclear Association. Nuclear Fusion Power. See https://world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx (accessed 31 May 2023).

7 UK Atomic Energy Authority. 2022 Our Strategy 2022-2026: Leading the delivery of sustainable fusion energy and maximising scientific and economic benefit. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1136256/Our_Strategy_2022-2026.pdf (accessed 31 May 2023).

8 Department for Business, Energy & Industrial Strategy. 2021 Towards Fusion Energy the UK Government's Fusion Strategy. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1022540/towards-fusion-energy-uk-government-fusion-strategy.pdf (accessed 31 May 2023).

9 UK Atomic Energy Authority. 2022 Our Strategy 2022-2026: Leading the delivery of sustainable fusion energy and maximising scientific and economic benefit. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1136256/Our_Strategy_2022-2026.pdf (accessed 31 May 2023).

10 Department for Business, Energy & Industrial Strategy. 2020 The impact of the UK's public investments in UKAEA fusion research: Final report. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/937633/impact-uk-investment-fusion-research.pdf (accessed 31 May 2023).

The UK government primarily support the private fusion sector through the UKAEA with four different schemes: Challenge (£12m), Equity (£8m), Voucher (£0.9m), and Education (£0.34m)[11]. Other countries with established investment in the fusion industry include USA, France, Germany, Russia and Japan[12]. The EUROfusion is a collaboration of European fusion laboratories, to which the EU has contributed €679million[13]. Japan recently announced a national strategy for fusion energy, with further support for private companies and start-up organisations one of its activities[14]. Active programmes are also under way in China, Brazil, Canada, and Korea[15].

In the USA, Congress is set to approve $763million in its 2023 budget for their Fusion Energy Sciences programme and $630million for inertial confinement fusion, making the USA government the highest funding government for the fusion sector to date[16]. The funding would support programmes such as the Innovation Network for Fusion Energy (INFUSE), which seek to provide financial and technical help to private businesses that partner with a fusion Department of Energy funded institution[17]. A $46million Milestone-based program has also been created to support for-profit organisations to successfully design fusion pilot plants[18]. The scale of the funding in the USA, and the diversity of the fusion research approaches at the national laboratories, are creating opportunities for different fusion approaches.

Inertial confinement fusion

Whilst the UK has focussed largely on tokamak fusion – currently the most common approach to confining plasma – there also exist other fusion technologies, one of which is 'inertial confinement fusion' (ICF). This is when the nuclear fusion process is initiated by rapidly compressing and heating a target filled with a fuel composed of deuterium and tritium (isotopes of hydrogen).

Research on ICF is underway around the world, including at the Lawrence Livermore National Laboratory and Sandia National Laboratories in the USA, the UK Atomic Weapons Establishment (AWE), the Laser Mégajoule (LMJ) built by the French nuclear science directorate (CEA), and at the ShenGuang-III laser facility in China. Universities also have ongoing research, including at the Laboratory for Laser Energetics (LLE) at the University of Rochester USA, Imperial College London and University of York in the UK, and Osaka University-Institute for Laser Engineering (ILE) in Japan. Private companies such as Innoven Energy, Marvel Fusion, and First Light Fusion have also begun research on ICF.

---

[11] Mooring L. 2022 Fusion Industry Programme. UK Atomic Energy Authority, 7th Supplier's Event. See https://ukaeaevents.com/wp-content/uploads/2022/04/Fusion-Industry-Programme-7th-Suppliers-Event.pdf (accessed 31 May 2023).

[12] World Nuclear Association. Nuclear Fusion Power. See https://world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx (accessed 31 May 2023).

[13] European Commission. Fusion Energy: Why the EU supports fusion research and innovation. See https://research-and-innovation.ec.europa.eu/research-area/energy/fusion-energy_en (accessed 31 May 2023).

[14] Fusion Industry Association. Japan Announces National Strategy for Fusion Energy. See https://www.fusionindustryassociation.org/japan-announces-national-strategy-for-fusion-energy (accessed 31 May 2023).

[15] World Nuclear Association. Nuclear Fusion Power. See https://world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx (accessed 31 May 2023).

[16] Fusion Industry Association. Congress Provides Record Funding for Fusion Energy. See https://www.fusionindustryassociation.org/congress-provides-record-funding-for-fusion-energy (accessed 31 May 2023).

[17] INFUSE (Innovation Network for Fusion Energy). What is INFUSE? See https://infuse.ornl.gov/what-is-infuse (accessed 31 May 2023).

[18] Energy.GOV. DOE Announces $46 Million for Commercial Fusion Energy Development. See https://www.energy.gov/articles/doe-announces-46-million-commercial-fusion-energy-development (accessed 31 May 2023).

POTENTIAL R&D BENEFITS

There are several key areas of science that HED R&D could facilitate. These include:

- Astrophysics – researching astronomical objects such as planets, stars, galaxies and the Universe
- Atomic physics – the study of the structure of the atom, its energy states, and its interactions with other particles and with electric and magnetic fields
- Cosmology – studying how the history of the universe led to the stars, galaxies, and other features we observe today
- Dynamic materials science – researching the response of materials at extremely high-energy densities
- Geophysics – the application of physics to study the interior of Earth and other planets
- Nuclear science – including AWE's nuclear research and the Ministry of Defence's hypervelocity studies
- Radiation physics – examining how radiation is transported through atoms in extreme conditions and its effects on components and systems

Recent breakthroughs in ICF at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory have demonstrated that more energy can be released from fusion than put directly into the target[19] [20] [21]. Advances in the UK have led to First Light Fusion creating a facility alongside UKAEA at the Culham Science Centre in Oxfordshire. First Light Fusion have focussed on building and testing a series of machines to fire a projectile at a fuel target to force it to fuse and produce energy. They are currently planning to build 'Machine 4' (M4) to take forward their ICF fusion ambitions. Such a machine has many potential basic and applied applications in the general area of high energy density (HED) physics.

For the UK Government, First Light Fusion's plans create options to facilitate partnerships and collaborations to maximise scientific R&D outcomes for the UK. As with any high-cost scientific infrastructure, application areas that have ongoing use considerations will require dialogue with the beneficiaries on investment and utilisation business models. The Government's current 'strategic advantage' technology assessment uses an 'Own-Collaborate-Access' framework, depending on the importance of the technology to the UK's strategic interests[22]. Whilst First Light Fusion plan to build M4 with private funding, this paper sets out the conclusions of the workshop with a view to informing relevant policy makers on the following questions:

- to what extent will First Light Fusion's HED facility complement the UK's existing global excellence and comparative advantage in fusion and its associated HED basic and applied scientific research possibilities?
- what are the current barriers for UK researchers to access or collaborate with HED and pulsed power facilities, and what is the case for access to a UK facility?
- how can the fusion & HED community assess and meet their future skills needs?

This study examined the breadth of potential research applications of a high energy density pulsed power device but has not examined, and so draws no conclusions on, the comparative research investment benefits between First Light Fusion's M4 and other fusion or non-fusion research infrastructure.

---

[19] A. B. Zylstra et al. 2022 Burning plasma achieved in inertial fusion. Nature 601, 542-548.

[20] Bishop B. 2022 Lawrence Livermore National Laboratory achieves fusion ignition. Lawrence Livermore National Laboratory. 14 December 2022. See https://www.llnl.gov/news/lawrence-livermore-national-laboratory-achieves-fusion-ignition (accessed 31 May 2023).

[21] LLNL (Lawrence Livermore National Laboratory). NIF Sets Power and Energy Records. See https://lasers.llnl.gov/about/keys-to-success/power-and-energy (accessed 31 May 2023).

[22] Cabinet Office. 2021 Global Britain in a Competitive Age: the Integrated Review of Security, Defence, Development and Foreign Policy. See https://www.gov.uk/government/publications/global-britain-in-a-competitive-age-the-integrated-review-of-security-defence-development-and-foreign-policy/global-britain-in-a-competitive-age-the-integrated-review-of-security-defence-development-and-foreign-policy (accessed 31 May 2023).

Key considerations from the workshop

To gauge the scientific community's interest in M4, and to better understand the design parameters that First Light Fusion might include to maximise the scientific benefits of M4, the Royal Society hosted an international workshop in November 2022 with experts across a variety of HED science fields.

If decision makers want to ensure M4 is as useful as possible to scientific research, designing and creating complex diagnostics as part of the facility will be required, and funding mechanisms for building and using M4 will need to be carefully considered as early as possible. Novel investment models may need to be created, with facilities such as Sandia and the National Ignition Facility (NIF) in the USA providing examples of collaborative funding options.

The HED physics community and relevant policy areas, including defence, will need to consider skills requirements to ensure that current and long-term education and skills policies support the UK's fusion ambition. As the private fusion industry expands, bringing a wide range of talents into the sector will be important. One way to achieve this could be increasing gender diversity in physics and engineering[23]. The Government's science and technology framework aims to deliver the skills needed to support a world-class workforce in STEM sectors and ensure a more diverse range of people work in science and technology[24].

Overcoming the practical challenges of procuring the engineering and technology requirements to build and maintain the M4 facility will involve complex risk management. Elements of M4 will likely need to be purpose designed and built, which could result in supply challenges, particularly if other facilities globally are building similar machines concurrently.

A UK-based facility would provide opportunities for collaboration with other countries, attracting further investment in UK-based science and technology. Additionally, the contribution of inertial confinement fusion to strengthen the wider fusion ecosystem should be considered.

Background to the workshop

A workshop exploring the potential of the M4 machine

On 28 November 2022, the Royal Society, in partnership with First Light Fusion, hosted 'Exploring the potential: A high energy density pulsed power device as a UK R&D platform'. The day-long hybrid workshop comprised presentations and audience discussions to explore the possible research applications for a new UK capability for high energy density science.

The meeting aimed to:

- inform the international science community that the world's largest pulsed power platform is planned to be built in the UK in the next five years.
- identify the science community interest in accessing this machine and what applications are of interest, exploring novel and fundamental science applications in these high energy density regimes.
- discuss the technical aspects, practicalities and logistics of what is needed to encourage and support access to First Light Fusion's machines or simulation codes and to promote collaboration.

This is not a verbatim record of the meeting, but a summary of the presentations and key points raised.

Pulsed Power

Pulsed power operates through accumulating electrical energy over a long period of time to a high capacity, and then releasing it as fast as possible into a very small volume, thus enormously increasing the instantaneous power and energy density. The resulting burst of energy can replicate conditions at the centres of stars and can be used to create nuclear fusion reactions.

The Z machine at Sandia National Labs in the USA is currently the largest pulsed power machine in the world. It uses high magnetic fields associated with fast, intense electrical currents to produce high temperatures, high pressures, and powerful X-rays for research in HED physics – focussing on defence applications and fundamental science research.

---

[23] Royal Academy of Engineering. 2019 Engineering skills for the future. See https://raeng.org.uk/media/hn4hdep3/perkins_report_jan19_final-web.pdf (accessed 31 May 2023).

[24] Department for Science, Innovation & Technology. 2023 The UK Science and Technology Framework Taking a systems approach to UK science and technology. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1140217/uk-science-technology-framework.pdf (accessed 6 June 2023).

A Potential New Capability ‘M4’

In five years, First Light Fusion plans to commission the largest pulsed power machine in the world, ‘Machine 4’ (M4) to produce high energy density plasmas with unprecedented, extreme physical conditions. Working designs for M4 indicate a stored electrical energy of ~100 MJ with peak output current of ~50 MA and a pulse duration of ~400 ns zero-to-peak. Sandia’s Z machine uses currents of about 26 MA to reach peak X-ray emissions of 350 TW and an X-ray output of 2.7 MJ[25].

The primary use of the M4 machine, if built, will be to demonstrate fusion energy gain using First Light Fusion’s approach to ICF. However, a high energy density pulsed power machine could be used for other areas of R&D, providing additional benefits for the UK science and innovation.

The Royal Society

The Royal Society is a Fellowship of many of the world’s most distinguished scientists drawn from all areas of science, engineering, and medicine. The Society’s fundamental purpose, as it has been since its foundation in 1660, is to recognise, promote, and support excellence in science and to encourage the development and use of science for the benefit of humanity.

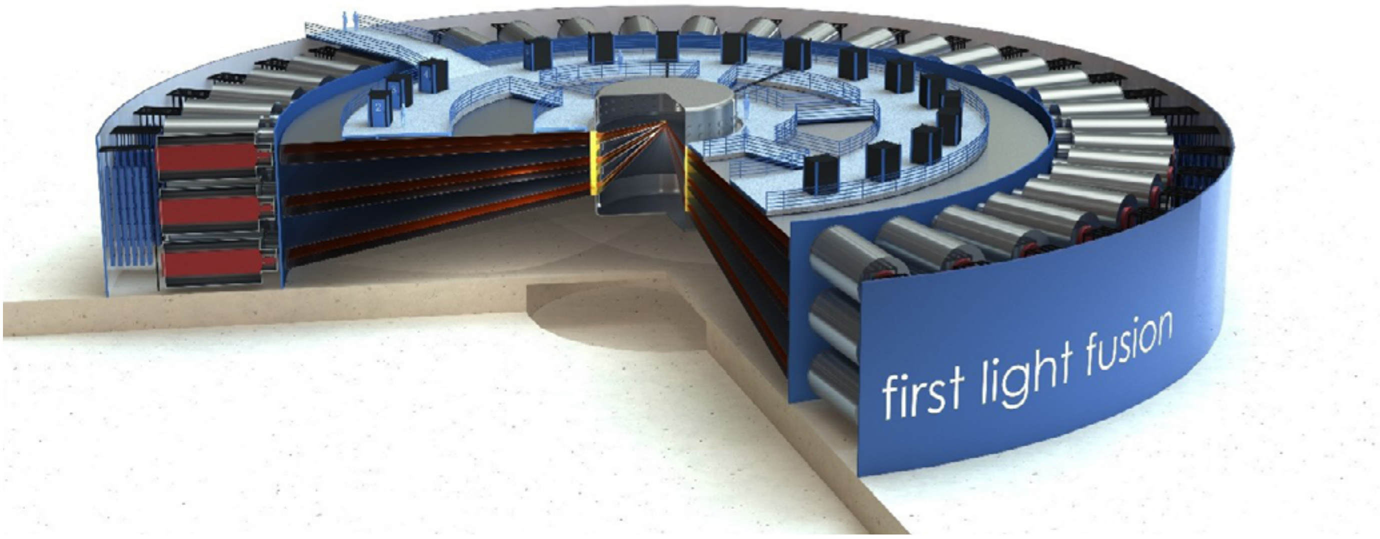
First Light Fusion

First Light Fusion is a privately funded fusion research company based in Oxfordshire, UK. They perform research in inertial confinement fusion using in-house capabilities such as two-stage light gas guns (the BFG launcher) and pulsed-power drivers (the M3 facility). In 2022 they produced fusion neutrons in a proof of principle experiment to show that a projectile driver, coupled to a pressure multiplying ‘amplifier’, can deliver sufficient energy to deuterium tritium gas to cause it to undergo fusion[26]. Their next challenge is to scale this up with plans to build a new machine, M4.

First Light Fusion’s in-house capabilities also include a large suite of software-based tools which bring together: high-fidelity simulation, data science, machine learning, and engineering design approaches. They were essential for designing the proof of principle experiment and are now being extended to support all aspects required to design and optimise an inertial fusion energy system. First Light Fusion’s technologies are being employed to support the design of fundamental science experiments on external facilities.

FIGURE 1

Machine 4 concept design is a Marx bank architecture based on an approximately 75m diameter cylindrically symmetric geometry.



---

[25] Sandia. Z Pulsed Power Facility: About Z. See https://www.sandia.gov/z-machine/about-z/ (accessed 6 June 2023).

[26] First Light Fusion. First Light achieves world first fusion result, proving unique new target technology. See https://firstlightfusion.com/media/fusion (accessed 31 May 2023).

Workshop discussion

Does the UK need a high energy density pulsed power facility?

Fusion

The initial primary use of M4 will be to demonstrate First Light Fusion's goal of fusion energy gain. If successful, it would greatly bolster the attraction of using pulsed power for fusion energy.

M4 could be used to test competitive fusion approaches, however only First Light Fusion's design for the machine is being considered. Accommodating alternative approaches is possible but would create added engineering risks to an already complex process.

Pulsed power

Originally at the forefront of public research into pulsed power technology[27], the UK now has only three universities with pulsed power capabilities. Imperial College London is home to, among other pulsed power machines, the largest University-based pulsed-power generator (MAGPIE) and researches the physics of wire array Z-pinches as an X-ray source, dynamics of gas-filled liners for magnetised liner inertial fusion (MagLIF) and the formation of supersonic, magnetised plasma flows and shocks for laboratory astrophysics. The High Voltage Technologies group at the University of Strathclyde Glasgow is leading research into techniques for ultra-fast switching and high peak power devices as well as the development and implementation of new industrial applications of pulsed power technology. Loughborough University carries out research in many sectors where pulsed power could be of benefit but focuses mainly on Radio Frequency Directed Energy Weapons (RF-DEWs).

Pulsed power is also being used as a tool to access high energy density regimes of plasma physics. Experiments include producing X-rays for inertial confinement fusion, recreating the conditions inside extreme astrophysical phenomena and observing fundamental processes in magnetised high-energy-density plasmas.

This reduction in pulsed power research will become more apparent when Sandia National Labs in the USA build a new pulsed power machine. First Light Fusion's M4 could create new opportunities for UK-based and international collaborations between academia and industry, so it is a useful point for the UK to consider its longer-term pulsed power strategy.

UK R&D

Other uses for M4 outside of fusion and pulsed power could have tangible benefits for scientific R&D in the UK, if it is designed with certain features and diagnostics. Such design features may require trade-offs, and so there is a case for early dialogue on the potential for collaborative funding and utilisation business models, to navigate optimal trade-offs between beneficiaries. Similar machines at Sandia in the USA do just that, resulting in a multi-purpose facility beneficial for many areas of scientific R&D. The presentations during the workshop highlighted several areas of potential interest. These include using burning plasma for astrophysics and cosmology to provide predictions on photo-ionised plasmas at a galaxy or quasar level. Spectroscopy and atomic physics could also benefit from a HED plasma machine, as could the study of magnetic fields and radiation physics. Materials science, especially the study of dense materials and their predicted structures, could benefit from experiments using M4 to corroborate complex computational models and theory.

---

[27] Smith I. 2006 The Early History of Western Pulsed Power. IEEE Transactions on Plasma Science 34, 1585–1609. (doi:10.1109/TPS.2006.883391)

Other uses discussed include gaining a better understanding of experiments currently being proposed or already underway, such as comprehension of interaction with light, and light on light experiments. These include particle physics, non-standard model physics, and other elements of fundamental physics outside of astrophysics and cosmological applications.

However, clarity of both the near-, mid- and long-term uses is needed to establish the value M4 could add, the relevant design requirements of M4, the timeline to use, and other necessities for each area of research. A realistic plan for potential use cases would be complex, and likely need to be collaborative between academia and government organisations, such as the Science and Technology Facilities Council.

Refining Diagnostics

State of the art diagnostics will be critical for any fusion machine to be useful as a research facility. Well calibrated time-of-flight neutron and activation detectors and complimentary pinch dynamic diagnostics, such as framing and streak cameras, are a few of the diagnostic requirements already being considered.

Who might use M4?

The UK's pulsed power capability at university-level is small, so collaboration opportunities are currently limited. M4 could establish more career opportunities and expand the requirement for experts, not just in fusion and pulsed power technologies but also cross-cutting fields such as diagnostics, lasers, engineering, and other scientific research. This could provide a significant augmentation to the UK HED talent ecosystem expanding human resources to collaborate with international counterparts and create knowledge-sharing opportunities.

Some systems are already in place to encourage this knowledge sharing. For example, the UK Laser Inertial Fusion Consortium aims to enable collaboration among the 11 UK inertial fusion institutions. They hope to act as a common voice for the membership, to develop strategies for fusion - including the UK Inertial Fusion roadmap - and to facilitate dialogue with the UK Government and international initiatives. A Pulsed Power Consortium is also being created, mainly between the UK and the USA, to collaborate on new pulsed power technology. Continued work in this area would be necessary to ensure the national benefits of a HED pulsed power machine could be achieved.

Summary of workshop presentations

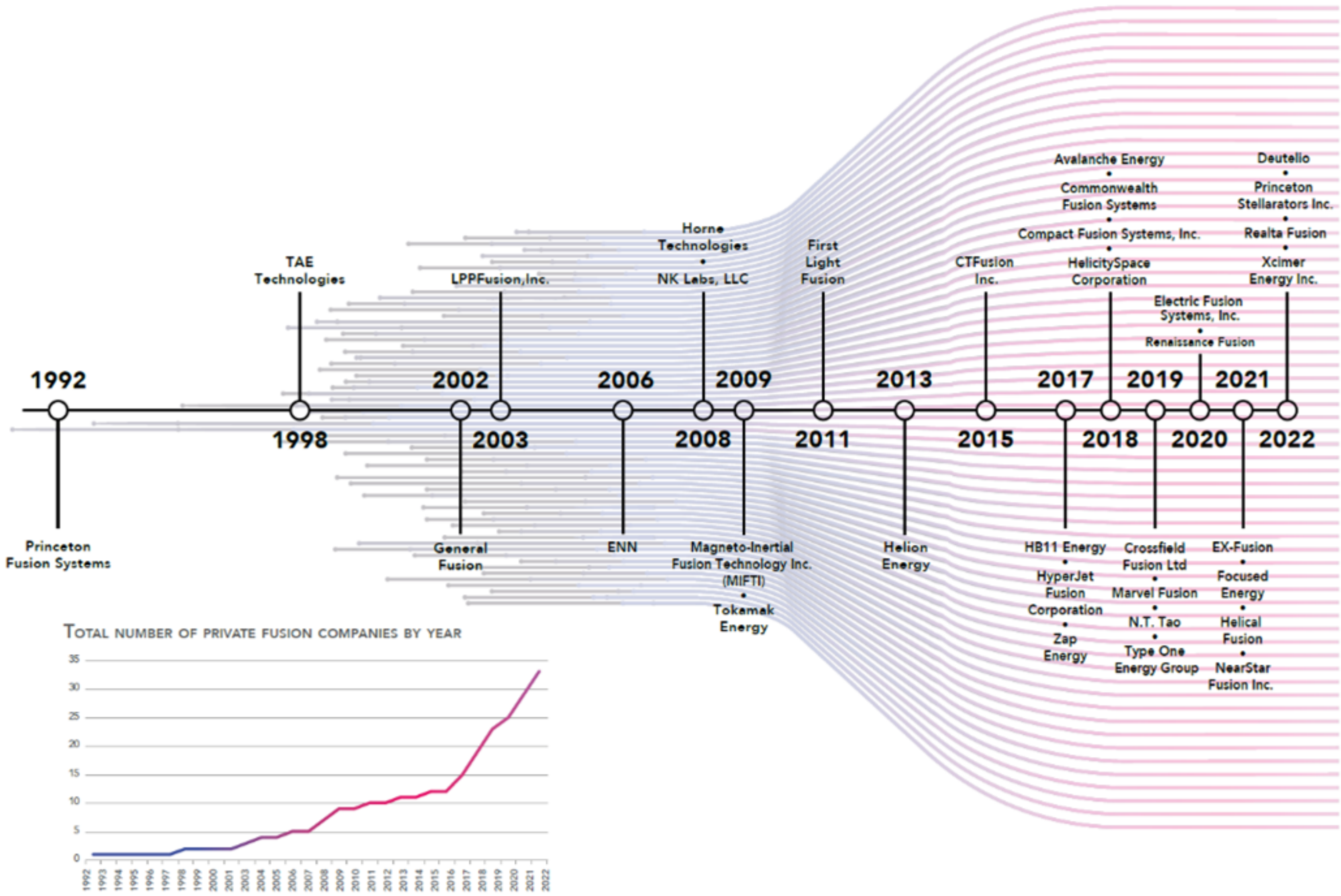
Professor Paul Monks, Chief Scientific Adviser at Department for Business, Energy and Industrial Strategy (BEIS), discussed the role for fusion from a BEIS perspective

The UK is a science superpower with regards to fusion, having previously invested in the technology at scale, and the Government wants to continue supporting commercial leadership in high energy science as the technologies progress.

Recent advances in fusion technology, driven by science and commercial work, means that achieving commercial fusion now feels closer than ever before. Whilst key scientific challenges remain, including fuel handling, system integration and innovative engineering, research is underway to overcome these issues using ambitious engineering. Although fusion technology is unlikely to make a large-scale, significant net-zero contribution before 2050, private sector innovation may reduce previous timelines and commercial fusion represents considerable future export opportunities for the UK.

FIGURE 2

Fusion companies founded in the last 30 years. Fusion Industry Association 2022 Global Fusion Energy report, Fusion Industry Association.



Published in 2021, the UK Government's fusion energy strategy has two major goals: for the UK to demonstrate the commercial viability of fusion, and to build a world-leading fusion industry that can export fusion technology around the world[28]. Growth in the sector has been rapid in recent years, with continued investment enabling an increase in skills and knowledge. To achieve the Government's goals and continue the growth in fusion, a connected ecosystem is required where Government, private industry, national laboratories, and academia work collaboratively with a systems-based approach. Within this, the UK Government has multiple roles, including creating markets, building networks, and growing and retaining talent.

Nick Hawker, Founder and CEO of First Light Fusion, discussed First Light Fusion's new pulsed power facility and the opportunities for collaboration

First Light Fusion's aim is to create commercial fusion energy. Currently, the focus is on the design of Machine 4 (M4) to demonstrate fusion energy gain, which will then influence the design of a pilot fusion energy power plant. The objective of the gain demonstrator machine is to remove the risk of the physics of self-heating, which is the biggest physical transition needed to build a fusion power plant. The M4 design is not fixed and is currently in its fourth iteration, and key risks, including manufacturing requirements and safety elements of the machine, need to be considered.

First Light Fusion use a high-velocity projectile as a new driver for inertial fusion. The projectile is launched in a target using electro-magnetic energy, which is accumulated using a large, pulsed power machine. The target is the key novel technology for First Light Fusion, as it is designed to compensate for the slow-delivery, low-power projectile by boosting the projectile's velocity and creating convergence, resulting in a very high-density state of matter in the target.

Collaboration on the M4 design, diagnostic development and core plasma physics is essential to make M4 an useful collaborative opportunity for fundamental science. Contributing to the growth of the available talent pool for fusion is also a priority, as well as designing a broad academic access programme which includes the use of other First Light Fusion machines, numerical codes and machine learning techniques.

Advancing current research

Sergey Lebedev, Professor of Plasma Physics and a Head of Plasma Physics Group at Imperial College London, provided an overview of fundamental science of MAGPIE and the prospects for new scientific discovery on a larger scale UK pulsed power platform

The Mega Ampere Generator for Plasma Implosion Experiments (MAGPIE) at Imperial College London is a pulsed-power generator, capable of delivering an electrical current pulse of ~1.4 million Amperes in ~250 nanoseconds. MAGPIE can create microscopic quantities of matter in conditions that replicate the centre of the sun, which can be used to perform scaled laboratory experiments of astrophysical hydrodynamics. The large magnetic fields generated at the facility can be used to accelerate, compress and heat the plasma. Through these experiments, it is possible to connect the astrophysical system observed, the laboratory testing systems, and the analytical and numerical models used.

Whilst MAGPIE is the largest university-based pulsed power generator, larger machines with relevant diagnostics would allow better scaling and longer evolution times to study non-linear stages of magneto-hydrodynamic systems. Larger machines would also allow studies of matter at astrophysical conditions and to improve understanding of matter behaviour in high pressure conditions, radiation transport, X-ray spectroscopy and atomic physics models. A more powerful pulsed power facility would also benefit high performance computer modelling in plasma physics and could contribute to validating computer codes for applications such as space weather, defence and fusion energy.

---

[28] Department for Business, Energy & Industrial Strategy. 2021 Towards Fusion Energy the UK Government's Fusion Strategy. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1022540/towards-fusion-energy-uk-government-fusion-strategy.pdf (accessed 31 May 2023).

Yitzhak Maron, Professor in the Faculty of Physics at Weizmann Institute of Science, Israel, discussed pulsed power machines as a tool for development of spectroscopic diagnostics for HED plasmas

Spectroscopic diagnostics for high energy density plasmas enable in depth knowledge of plasma behaviour at high densities and extreme temperatures. Previous and current experiments revealed that during stagnation in z-pinch implosions (a plasma confinement approach where electric currents are used to generate a magnetic field that compresses the plasma itself) only a fraction of the ion kinetic energy is thermal, leading to changing the understanding of energy balance between thermal motion and hydro motion. However, experiments using a higher current pulsed power machine would allow access to the spectroscopic measurements of much hotter plasmas with inertial confinement fusion densities.

Methods are already being developed to be used on higher current machines, and the results would provide better insights of electron temperatures, current densities, charge states and magnetic field distributions in z-pinch implosions. Experiments on a high current machine could also benchmark results from recent magnetised liner inertial fusion (MagLIF) experiments at Sandia and similar research at the National Ignition Facility (NIF). The opportunity to develop research in radiation-matter interaction and improve spectroscopic techniques with high current machines is motivating for those working in relevant areas of physics.

Stephanie Hansen, Senior Scientist at Sandia National Laboratories and a Visiting Associate Professor at Cornell University, discussed how pulsed power has advanced our understanding of fundamental radiation and atomic physics

Pulsed power is an engine of discovery for atomic physics and astrophysics. Sandia’s Z machine can create relatively large samples of plasma at extreme temperatures and densities, reaching conditions found in stars and fusion plasmas. These plasmas can be studied using X-ray spectroscopy, which separates light along an energy axis to reveal the electronic structure of atoms embedded in extreme environments.

Already, pulsed power has led to discoveries in atomic physics. Experiments on Sandia’s Z machine using pulsed-power-driven magneto-inertial fusion provided information about how radiation is transported through material in extreme conditions. Observing fluorescent spectroscopy of iron plasmas gave surprising results that were different to anything previously observed, resulting in a better understanding of electronic structure in dense plasma.

Pulsed-power-driven X-ray experiments have also enabled benchmarking experiments relevant to astrophysical sources. Currently, the Z machine is the standard-bearer for benchmark-quality opacity measurements. Using the Z machine, it is possible to carry out research in more extreme conditions than previously possible, revealing unexpected disagreements between some experimental results and atomic models. Ongoing experiments are continuing to better understand the reasons behind the disagreements and advance understanding of the structure of our sun.

A future machine, such as M4, that could be used more frequently would make progress more rapid as pulsed power is an excellent tool to advance our knowledge of the universe. Coupled with spectroscopy, it is possible to better understand phenomena from quantum mechanics to astrophysics and fusion sources necessary to control and harness fusion energy. Scientific discoveries – and surprises – will continue as facilities enable experiments at more extreme conditions.

Future research possibilities

Steven Rose, Head of Plasma Physics and the Vice-Dean of Natural Sciences at Imperial College London, presented on scientific applications of burning plasmas for fundamental physics studies

High energy density laboratory astrophysics examines the connection between interpretative theories from laboratory experiments using high-powered lasers or pulsed power machines with various aspects of astrophysics and cosmology, including planetary interior science, magnetic field generation, particle acceleration, solar and stellar radiative opacity and photoionised plasmas. However, there are several experiments that are possible with burning plasma that are not possible with currently available facilities, as the temperatures and densities that could be obtained inside a burning plasma are more extreme than using lasers or a pulsed power machine without a target. Burning plasmas provide access to the most extreme macroscopic environment ever created in the laboratory.

Burning plasma is critical for two types of experiments. The first would use the burning plasma itself, and could research Compton scattering, double-Compton scattering, electron-positron production from thermal plasma, nuclear reaction rates in a hot dense plasma and slow or rapid nuclear processes from high neutron flux. These experiments could be used to provide a better understanding of the construction of the universe and the early universe, as well as other areas of astrophysics. The second type of experiment would use the output from burning plasma and includes research on photoionised plasmas to interpret stars' spectrums, opacity experiments at high temperatures and densities, line-coincidence photopumping from astrophysics, and experiments relevant to fundamental physics. Overall, burning plasma research could create a step-change in our ability to test models from particle physics, through astrophysics and on to cosmology.

Robbie Scott, Senior Plasma Physicist in the Central Laser Facility at the Science and Technologies Facilities Council, provided an overview of Laser Inertial Fusion science and areas where HED pulsed power can contribute

In laser inertial fusion, a capsule containing deuterium–tritium fuel is heated using lasers. This creates very high pressure in the centre of the capsule and causes a fusion reaction, which is confined in the capsule by its own inertia. NIF currently leads inertial research using laser fusion and anticipates fusion energy-gain in the next three years. NIF ignition has demonstrated the key inertial fusion physics using 'indirect drive', where lasers are aimed around the fuel capsule to uniformly drive the implosion. However, this method is inefficient, complex and results in material activation. An alternative method, 'direct drive', aims the laser beams directly at the capsule. This has the benefits of being four times as efficient as indirect drive (meaning a smaller and cheaper laser could be used) and needs a simpler target (resulting in easier mass-manufacturing). However, some physics uncertainties remain for the direct drive approach. Experiments are ongoing to remove the limitations of existing laser fusion concepts, including using Shock Augmented Ignition to remove the high intensity requirement needed to launch the shock.

There are many advantages of inertial fusion energy. Firstly, the modular components containing complex technology are far away from the fusion plasma to reduce potential neutron and thermal damage and simplify reactor maintenance. Secondly, specifically with laser fusion, the technology is modular and can therefore be developed rapidly in parallel. Finally, there is reduced tritium inventory and possibly reduced capital expenditure.

Areas of overlap between inertial fusion energy and HED pulser power could be potential research topics for M4. Inertial fusion energy needs certain physics requirements, including implosion sphericity, hydrodynamic stability, drive pressure and fuel entropy. Research questions relevant to M4 therefore include whether having one impact point is sufficient in the M4 design and calculating the potential risk of having macro-scale instability in growth measurements. System requirements are also needed for both systems, including capital, operational and maintenance costs, as well as energy efficiency. Crucially, these requirements must all be compatible with viable physics.

Robert Lock, Head of Physics at the Atomic Weapons Establishment, presented on defence and deterrent relevant HED science

The Atomic Weapons Establishment (AWE) has a mission to deliver nuclear warheads for the UK's deterrent and use its expertise to support national security. It is no longer possible to test and certify the UK's nuclear deterrent directly to guarantee safety and performance of the nuclear stockpile. As such, the stockpile must be tested indirectly by exploring the scientific underpinnings of the deterrent. This is carried out partly through HED plasma experiments to get a detailed understanding of the physics related to nuclear devices.

In addition to validating AWE's models and judgements for indirect stockpile testing, HED pulsed power experiments have many current and future uses for AWE. These include research areas such as examining materials science and properties under extreme conditions, integrated radiation hydrodynamics, burning plasmas, atomic physics, effects of radiation on components and systems and system effectiveness. Currently, the tools available for these experiments – including the Z machine and NIF in the USA, as well as AWE's own facilities – are key to AWE's work but cannot reach the regimes of direct interest. Therefore, having access to a system that can create accurate conditions would increase AWE's certainty of safety and performance of the UK's nuclear deterrent. It would also be important for a new HED pulsed power facility to have a broad range of diagnostic capability and useful load designs and technologies – as the Z machine has – built in collaboration with potential users.

Overall, there is strong potential for AWE to collaborate on and benefit from M4, especially if First Light Fusion were able to achieve target energy fusion gain. Multiple applications of M4 would be relevant to AWE if M4 has load flexibility, the ability to integrate AWE diagnostics and the ability to operate to meet the Ministry of Defence's security requirements. Crucially, M4 could be an opportunity to grow a pool of specialists in the UK and create an opportunity for collaboration with relevant organisations if sufficient resources are in place for people to grow and maintain the necessary expertise.

Chris Pickard, Sir Alan Cottrell Professor of Materials Science in the Department of Materials Science and Metallurgy, University of Cambridge discussed first principles exploration of dense materials

At an atomistic scale, the behaviour of dense materials is still relatively unknown. A range of apparatus is necessary to replicate different pressure scales that might be encountered in the universe currently and historically, and it is not possible to achieve higher pressures with current facilities. Whilst computational theory can make predictions, machines that could provide the necessary experimental techniques could provide empirical data for dense material structure at extremely high pressures.

Carrying out experiments on atom structure is difficult, and analysing the results is also difficult, so theoretical structure predictions are useful for applications of materials science. Computational theory has advanced in recent years to create robust structure predictions for materials and different scales and densities. Using machine learning, simulations of certain materials at high pressures have discovered unpredicted material behaviours. A recent example is the predicted, theoretical discovery of four new thermodynamically stable phases of carbon at high pressure[29]; particularly relevant for ICF fusion which uses high carbon content materials for the target capsule. Chemical reactions have also been theoretically predicted to act differently at higher pressures. Therefore, a machine such as M4 could provide empirical data on the behaviours of dense materials, either supporting or contradicting the first principle's structure predictions.

---

[29] Martinez-Canales M, J. Pickard C, J. Needs R. 2012 Thermodynamically Stable Phases of Carbon at Multiterapascal Pressures. Physical Review Letters 108, 045307. (doi:10.1103/PhysRevLett.108.045704)

Building capacity

Kate Lancaster, senior lecturer and former programme leader for the MSc in Fusion Energy at the University of York's Plasma Institute, presented on the York Fusion Doctoral Training Centre's interactions with external facilities

The greatest threat to fusion success is not having enough well-trained people in the sector. A diverse range of people is needed to work in the diverse range of organisations relevant to fusion. Furthermore, diversity is essential for equity and fairness to be incorporated into the creation of fusion energy from the start. In the last decade the fusion landscape has changed significantly, and the workforce needs to reflect that; training people is key.

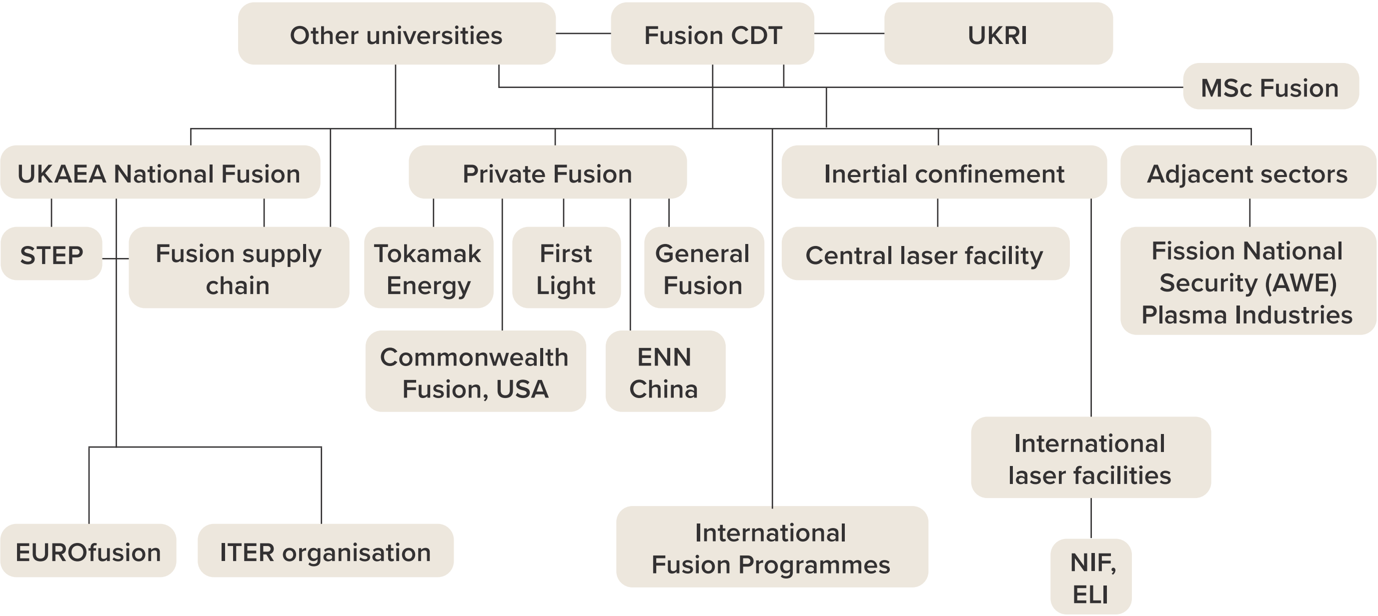
The Centre for Doctoral Training (CDT) is a four-year PhD programme, run by a network of five universities led by the University of York, and collaborates with national and international laboratories and industry, including private fusion companies and the wider supply chain. The CDT course focuses mainly on plasma physics and material science, although the advancements towards building and operating fusion prototypes has resulted in growing the social science expertise in regulation and licensing, public acceptability, and fusion economics. The aim of the CDT is to train the next generation of fusion experts, including those who support private fusion companies to drive the faster delivery of fusion power. The CDT is currently in its final year, with funding unconfirmed for future programmes.

There are many ways the CDT interacts with external facilities and partners, including CDT events that industry partners are involved in creating, external partners funding PhDs or delivering part of the training programme, and relevant experts sitting on the external advisory board. Experiments on external facilities are also a large part of maintaining relationships with external partners.

Future plans for the CDT involve maintaining external partner's key involvement in the training programme by deepening existing relationships, including the use of M4, and creating new ones. There are many areas of overlap with HED science, including theory and simulation, diagnostic development and laboratory astrophysics, which could be beneficial for industry and students. Ultimately, ensuring there is a sufficient supply of well-trained, fusion-literate people across a large range of areas is key.

FIGURE 3

The Need: Fusion skills required across diverse organisations, in the UK and Internationally



Source: Fusion CDT.

Dan Sinars, Director for the Pulsed Power Sciences Center and Sandia National Laboratories, discussed pulsed power at Sandia National Laboratories and the Z fundamental science program

Sandia currently has the world's largest pulsed power machine, the Z machine, which can generate a central pressure equivalent to between Jupiter's and the sun's core pressure. The target hardware in the centre of the machine can change, as it gets destroyed with every use. As a result, it can be used for material experiments, producing X-rays and fundamental plasma physics.

Approximately 15% of the Z machine use is for basic research of relatively novel science. Through this, Sandia have created close links with academia, and often peer reviews academic work. In 2010 the Z Fundamental Science Program was created as a path for universities and industry to collaborate with Sandia. The program is supported by National Nuclear Security Administration (NNSA) and allows up to 10% of the Z machine shots to be used for the program, with operational costs paid for by NNSA. External researchers using the Z machine are required to support themselves, often through a research grant. Sandia is currently working with the NNSA on the design of a new pulsed power machine, to be completed in the late 2030s, with the aim to be the world's most powerful warm X-ray source and provide advanced capability for high energy density physics. Sandia are open to collaborating with First Light Fusion on the creation of the new pulsed power machine, especially as First Light Fusion has the potential benefit of a quicker process to building the machine with private investor support.

The Royal Society is a self-governing Fellowship of many of the world's most distinguished scientists drawn from all areas of science, engineering, and medicine. The Society's fundamental purpose, as it has been since its foundation in 1660, is to recognise, promote, and support excellence in science and to encourage the development and use of science for the benefit of humanity.

The Society's strategic priorities emphasise its commitment to the highest quality science, to curiosity-driven research, and to the development and use of science for the benefit of society. These priorities are:

- The Fellowship, Foreign Membership and beyond
- Influencing
- Research system and culture
- Science and society
- Corporate and Governance

For further information
The Royal Society
6 – 9 Carlton House Terrace
London SW1Y 5AG

T +44 20 7451 2500
E science.policy@royalsociety.org
W royalsociety.org

Registered Charity No 207043

Issued: September 2023 DES8298_4