INERTIAL FUSION BREAKTHROUGH: WHAT IT MEANS FOR FUSION ENERGY

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A major milestone on the journey to fusion energy was realised by a team at the Lawrence Livermore National Laboratory (LLNL), USA on the 5th of December 2022, on the National Ignition Facility (NIF). For the first time in any fusion experiment the team demonstrated getting more fusion energy out from the fusion reactions than was input. This major scientific achievement was announced at a press briefing on the 13th December 2022 by the US Department of Energy's National Nuclear Security Administration (NNSA). This was a historic milestone and the culmination of decades of effort.

INTRODUCTION:

Fusion has the potential to provide humankind with a near infinite source of carbon free, safe, secure, and reliable baseload energy. The scientists at the NIF use high energy laser beams to compress and heat a pellet of fuel in a technique called Inertial Confinement Fusion (ICF). ICF is one of two extensively researched techniques to achieving fusion energy, the other main method being Magnetic Confinement Fusion (MCF) using Tokomaks. As realising fusion energy is so challenging, and the rewards of fusion energy so huge, scientists are actively pursuing both methods.

NIF's implosion produced a total of 3.15 MJ of fusion energy with 2.05 MJ of laser energy, demonstrating that the process can produce more fusion energy than the laser energy delivered to the target. This major milestone, showing a gain of 154%, follows a previous key achievement on NIF, demonstrating an igniting plasma on August 8, 2021. On that occasion the yield was estimated to be 72% of the laser input energy, with 1.35 MJ of fusion energy generated from 1.93 MJ of incident laser energy into the target [1].

The U.S. Secretary of Energy Jennifer Granholm at the DOE Press Conference Announcing Major Nuclear Fusion Breakthrough on December 13, 2022 stated "Last week at the Lawrence Livermore National Laboratory in California, scientists at the National Ignition Facility achieved fusion ignition. And that is creating more energy from fusion reactions than the energy used to start the process. It's the first time it has ever been done in a laboratory anywhere in the world. Simply put, this is one of the most impressive scientific feats of the 21st century." [2]

UK scientists played key roles in this work, both at UK institutions and within the LLNL team. Despite this, and extensive research expertise within the UK, there is currently no UK investment going into laser-driven ICF grant funding in the UK.

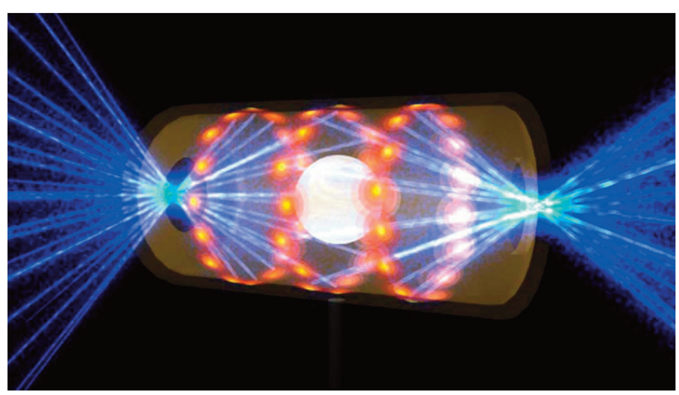

Figure 1: NIF Hohlraum: This artist's rendering shows a NIF target pellet inside a hohlraum capsule with laser beams entering through openings on either end. The beams generate X-rays that compress and heat the target to the necessary conditions for nuclear fusion to occur. Ignition experiments on NIF are the result of more than 50 years of inertial confinement fusion research and development, opening the door to exploration of previously inaccessible physical regimes. (Image copyright LLNL)

NIF uses the technique of indirect drive Inertial Confinement Fusion (ICF) where the millimetre scale capsule containing the nuclear fuel, a mix of deuterium and tritium, is enclosed in a gold cavity, the Hohlraum. The inner walls of the cavity are irradiated by the 192 NIF laser beams, giving rise to intense X-ray emission that ablates the outer surface of the capsule, accelerating the fuel inwards in a rocket-like behaviour. The following implosion makes the capsule shrink many times, compressing the fuel and increasing its density by up to 4000 times. It is designed to self-ignite (very crudely in a similar fashion to a car's diesel engine) when the compressed fuel achieves the required density and temperature to enable fusion reactions to start from a central hot spot and propagate outwards to burn the surrounding fuel.

HISTORY:

In seminal papers published in 1972, the concept of ICF was proposed both in the US and USSR[3, 4]. The US abstract stated that 'Hydrogen may be compressed to more than 10,000 times liquid density by an implosion system energized by a high energy laser. This scheme makes possible efficient thermonuclear burn of small pellets of heavy hydrogen isotopes and makes feasible fusion power reactors using practical lasers.'

This began a global concerted effort, particularly in the US, for over 50 years to understand the physics behind ICF and finally demonstrate ignition. At LLNL a series of lasers were constructed from the mid-1970s with ever increasing energies and specifications: Janus and Cyclops in 1975; Argos in 1976; Shiva in 1977; Novette in 1983; Nova in 1984 and finally NIF[5]. A progression of the development of lasers; their optical systems; diagnostics for both lasers and plasmas; targets; and computer architectures and codes for simulation and prediction – all critical to the delivery of the ICF programme.

NIF[6], funded by the U.S. DOE's NNSA is the largest and highest energy laser facility in the world with a footprint occupying three football pitches. It comprises 192 beams, operating at 351 nanometres (blue light), delivering in total more than 2 MJ of energy which can be simultaneously focused on to a millimetre scale target placed at the centre of a 10 metre diameter vacuum chamber. Its design and construction started in the 1990s, with first light demonstrated in 2003, and conducted its first full-scale experiments in 2009. NIF is still the only facility globally that can conduct full scale ICF experiments.

WHERE NEXT:

In the perspective of future fusion energy production, achievement of ignition was considered by the scientific community as the key milestone required to enable the development of Inertial Fusion Energy production, aimed at the proof of principle demonstration and, eventually, a realistic concept of a power plant. In this process, LLNL is expected to continue with experiments on NIF, to demonstrate repeatability of ignition and hopefully enhanced gain.

The recent NIF demonstration is a "single shot event", demonstrating that the ICF concept works. The path to a fusion power plant will require developing lasers with higher shot repetition rate and efficiency (the UK's STFC Central Laser Facility are world leaders in this). There are also alternative, more efficient schemes including direct-drive, where the lasers interact with the fuel capsule directly, which will also be investigated. The direct-drive key processes are shown in Figure 2.

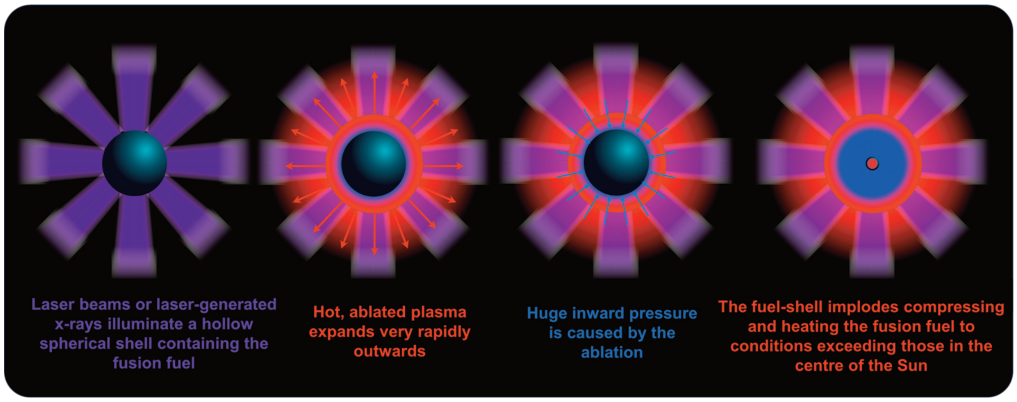

Figure 2: The stages of direct-drive Inertial Confinement Fusion

It will also be necessary to address many other aspects required for energy production including: target manufacturing and delivery; first wall materials; and tritium breeding. These aspects were extensively discussed in the US Basic Research Needs (BRN) Workshop in June 2022[2] that was aimed at "exploring the science, technology, and investments needed to realize Inertial Fusion Energy (IFE)'s potential as a source of safe, clean energy in the coming decades".

These initiatives are also aimed at building the ecosystem required for the growing number of private companies to attract funding for the development of fusion schemes and technologies required for future power plants. It is expected that globally, inertial fusion energy research will receive a major boost by the recent advances at NIF and will lead to acceleration of existing national IFE programmes or establishment of new programmes.

Unfortunately, there is a lack of strategic funding for ICF in the UK and throughout Europe. This contrasts the situation with MCF, which has extensive governmental research funding. Research activities in ICF are funded through individual research grants and grass roots networking. In the UK, policy developments have helped push the UK's fusion industry forward for example by creating an agreement on the regulatory framework for future reactors, however the government published Fusion Strategy does not currently mention Laser Fusion. A UK ICF consortium (the UK Inertial Fusion Consortium) led by STFC includes 85 members from seven universities and AWE has developed a UK Roadmap focussed on Laser Fusion. The UK is seeking to start a new project called UPLiFT which will develop the technologies required to advance NIF's proof-of-principle experiment on the journey to Laser Fusion power production.

The UK is not isolated in this endeavour and interacts extensively with the global community. Europe is currently looking into the establishment of a comprehensive IFE project, HiPER+[7], following the approach developed in the previous HiPER project[8], which was led by the UK's Central Laser Facility. This is supported by novel ICF related experiments at existing laser facilities and extensive computer modelling. HiPER was based on the direct-drive scheme as it is more efficient than NIF's indirect-drive method, which is important for fusion power generation.

CONCLUSIONS

The recent achievement at NIF, namely the demonstration of fusion ignition with laser-driven inertial confinement fusion, is the successful outcome of a fifty-year journey starting with the seminal idea of Nuckolls and Basov in 1972. While a number of challenging scientific and technological open issues remain, the main uncertainty on the way to inertial fusion energy production, namely the validity of the ICF concept, has been removed and the journey can continue and aim at the next milestones.

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