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HIGH POWER LASER SCIENCE AND ENGINEERING

EDITORIAL

# Inertial confinement fusion ignition achieved at the National Ignition Facility – an editorial

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**Abstract**
On behalf of all at *High Power Laser Science and Engineering* we would like to congratulate the team at Lawrence Livermore National Laboratory (LLNL) on demonstrating fusion ignition at the National Ignition Facility. This major scientific achievement was realized on the 5 December 2022 at the LLNL and announced at a press briefing on the 13 December 2022 by the United States Department of Energy's National Nuclear Security Administration. This was a historic milestone and the culmination of decades of effort.

**Keywords:** inertial confinement fusion; fusion ignition; inertial fusion energy; high power lasers

## 1. Introduction

Based on the information provided during the press briefing, the details of this historical achievement are the following: the 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 of the National Ignition Facility (NIF), demonstrating the world's first burning plasma on 8 August 2021. On that occasion the yield was estimated to be 70% 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 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.

The US Secretary of Energy, Jennifer Granholm, at the Department of Energy (DOE) Press Conference Announcing Major Nuclear Fusion Breakthrough on 13 December 2022, stated the following[2]:

"Last week at the Lawrence Livermore National Laboratory in California, scientists at the NIF 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."

Lawrence Livermore National Laboratory (LLNL) Director Dr. Kim Budil, also at the DOE Press Conference Announcing Major Nuclear Fusion Breakthrough on 13 December 2022, stated the following[2]:

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"Breakthroughs like this one have generated tremendous excitement in the fusion community, and a great deal of private sector investment in fusion energy. But this is only possible due to the long-term commitment of public investment in fusion science. The science and technology challenges on the path to fusion energy are daunting but making the seemingly impossible possible is when we're at our very best. Ignition is a first step, a truly monumental one that sets the stage for a transformational decade in high energy density science and fusion research, and I cannot wait to see where it takes us."

## 2. History

In seminal papers published in 1972, the concept of ICF was proposed (Nuckolls *et al.*[3] from the then University of California Lawrence Livermore Laboratory, now LLNL; and Basov *et al.*[4], P. N. Lebedev Physical Institute, Moscow). The Nuckolls's abstract stated the following:

"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 USA, for over 50 years to understand the physics behind ICF and finally demonstrate ignition. At the LLNL, a series of lasers was 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 the NIF[5]. This represented 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.

The NIF[6], funded by the US DOE's National Nuclear Security Administration (NNSA), is the largest and highest energy laser facility in the world. It comprises 192 beams, operating at 351 nm, delivering in total more than 2 MJ of energy that can be simultaneously focused onto a millimetre-scale target placed at the centre of a 10 m diameter vacuum chamber (see Figure 1). Its design and construction started in the 1990s, with first light demonstrated in 2003, and it conducted its first full-scale experiments in 2009. The NIF is still the only facility globally that can conduct full-scale ICF experiments.

## 3. Where next

From the perspective of future fusion energy production, the achievement of ignition was considered by the scientific community as the key milestone required to enable the development of inertial fusion energy (IFE) production, aimed at the proof of principle demonstration and, eventually, a realistic concept of a power plant. In this process, the LLNL is expected to continue with experiments at the NIF, to demonstrate the repeatability of ignition and hopefully enhanced gain, which are equally important milestones for IFE.

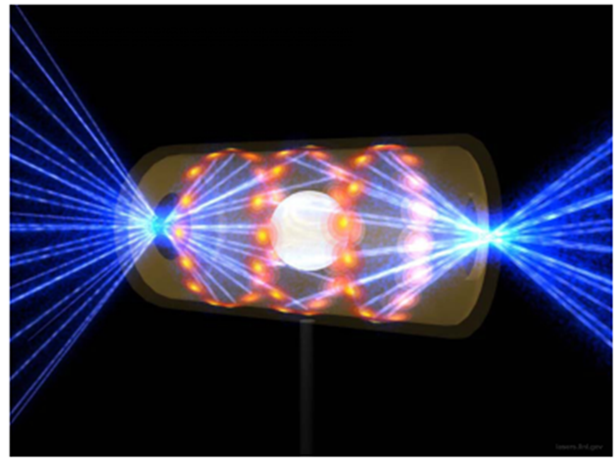

**Figure 1.** NIF hohlraum: this artist's rendering shows a NIF target pellet inside a hohlraum capsule with laser beams entering through openings on either end. The beams generate X-rays that compress and heat the target to the necessary conditions for nuclear fusion to occur. Ignition experiments at the 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: Lawrence Livermore National Laboratory).

The recent NIF demonstration is a 'single shot event', demonstrating that the ICF concept works. However, the path to a fusion power plant would require exploring alternative more efficient schemes and additional techniques to address many aspects related to energy production, including laser repetition rate and efficiency, target manufacturing and delivering, 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 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, IFE research will receive a major boost by the recent advances at the NIF that will lead to the acceleration of existing national IFE programmes or the establishment of new programmes.

Indeed, Europe is currently looking into the establishment of a comprehensive IFE project[7,8], following the approach developed in the previous HiPER project[9] and further supported by novel ICF-related experiments at existing laser facilities[10] and extensive modelling. The HiPER project was based on the direct-drive scheme with advanced ignition. Indeed, the classical direct drive scheme proposed originally has been extensively explored in the past, showing limitations due to the onset of hydrodynamic instabilities and laser-induced instabilities. These processes are responsible for a high level of laser light backscattering (stimulated Brillouin scattering (SBS)) and pre-heating of the compressed capsule due to fast electron generation. Advanced ignition schemes such as shock ignition[11] use the first phase of moderate compression followed by an ignition phase driven by a converging shock generated by a high-intensity laser spike at the end of the compression phase. This scheme is expected to achieve high gain with moderate laser energy[12] and is being considered for IFE research along with other advanced ignition schemes, such as fast ignition and magnetized linear inertial fusion. Similarly, other countries traditionally involved in ICF are redesigning their national programmes for IFE and developing their roadmaps for energy production.

## 4. Conclusions

The recent achievement at the NIF, namely the demonstration of fusion ignition with laser-driven ICF, is the successful outcome of a 50-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 IFE 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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