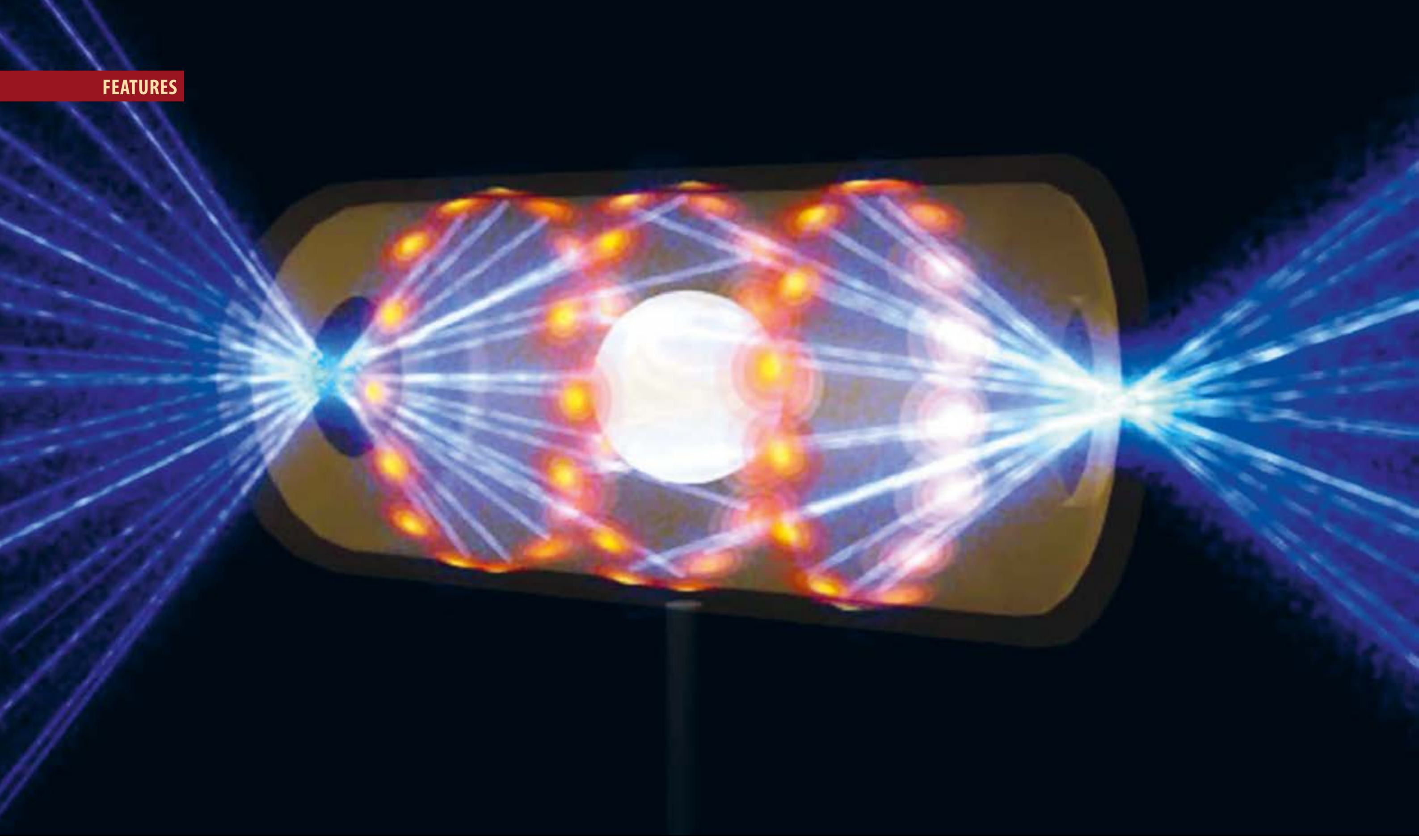

BREAKTHROUGH AT THE NIF
PAVES THE WAY TO INERTIAL FUSION ENERGY

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In August 2021, at the National Ignition Facility of the Lawrence Livermore National Laboratory in the USA, a 1.35 MJ fusion yield was obtained. It is a demonstration of the validity of the Inertial Confinement Fusion approach to achieve energy-efficient thermonuclear fusion in the laboratory. It is a historical milestone that the scientific community has achieved after decades of efforts.

The concept of laser-driven inertial confinement thermonuclear fusion (ICF) for energy production was proposed in 1972 in seminal papers [1,2] that initiated a worldwide effort to demonstrate inertial fusion ignition in the laboratory. After five decades of continuous progress toward ignition, in August 2021 the National Ignition Facility (NIF) of the Lawrence Livermore National Laboratory (USA), announced a major advance[1], with 70 % of the 1.93 MJ input laser energy converted into products of the deuterium-tritium fusion reactions, namely neutrons and alpha particles. The record 1.35 MJ of output fusion energy was eight times higher than the yield obtained in previous best measurements. With this result the ignition milestone, that requires the fusion energy yield to be equal to the input laser energy, is only a small step away, proving unambiguously the validity and the feasibility of the ICF concept.

The NIF indirect drive approach and the 1.35 MJ yield experiment

The National Ignition Facility (NIF) uses the so-called *indirect drive scheme* in which the capsule containing the nuclear fuel, a mix of deuterium (D) and tritium (T), is enclosed in a gold cavity, the Hohlraum[2] (Figure 1). The inner walls of the cavity are irradiated by the 192 NIF laser beams, giving rise to intense X-ray emission that ablates of the outer surface of the capsule, accelerating the fuel inwards in a rocket-like behaviour (Figure 2).

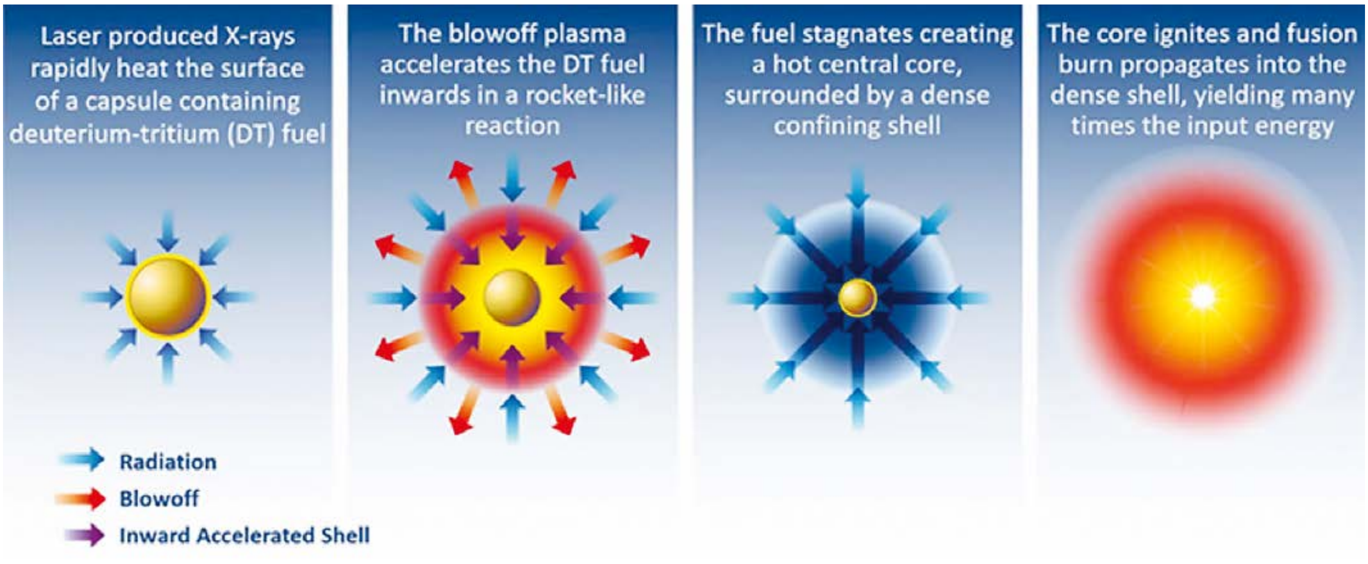
The following implosion makes the capsule shrink many times, compressing the fuel inside and increasing its density by up to about 1000 times, and heating its central part, the so-called hot-spot, to a temperature higher than 5 keV, needed to initiate copious D-T fusion reactions, each of which releases a 14.1 MeV neutron and a 3.5 MeV alpha particle. The alpha particles produced by the D-T reactions are slowed down in the compressed fuel, further heating it and compensating the losses due to radiation and heat conduction. In these conditions, a burn wave propagates out of the hot-spot into the surrounding compressed fuel and a large amount of fusion energy can then be released.

Different configurations have been designed and tested at NIF showing that a number of manufacturing issues play a crucial role in the implosion performance. Progressive control of these parameters enabled scientists to achieve successive improvements in the target design that finally led in August 2021 to an extraordinary performance in terms of neutron yield. In Figure 3 the neutron yield is shown as a function of the total hot-spot internal energy obtained from the series of implosion campaigns with different configurations. The campaigns were carried out during the past ten years. The red markers in Figure 3 indicate the major progress emerged with the High-Yield Big-Radius Implosion Design (Hybrid-E, HyE) [3]. In the figure the August 8, 2021 shot reached a total hot-spot internal energy of 65 kJ, of which 45 kJ due to self-heating from fusion reaction, yielding the production of 4.8×10^{17} neutrons and alpha particles, for a total energy of 1.35 MJ.

The high energy yield was possible thanks to the occurrence of the alpha heating mechanism. For the first time at NIF, the alpha particles generated by the fusion process were efficiently stopped in the compressed fuel, giving rise to a further heating of the

◂ **FIG. 1 - P.20:** An artist's rendering shows how the National Ignition Facility's 192 beams enter a small-size cylinder of gold and heat it from the inside to produce x-rays, which then implode the fuel capsule at its centre to create fusion. Credit: Lawrence Livermore National Laboratory

▾ **FIG. 2:** The phases of ICF including laser heating, compression, hot-spot creation and ignition.



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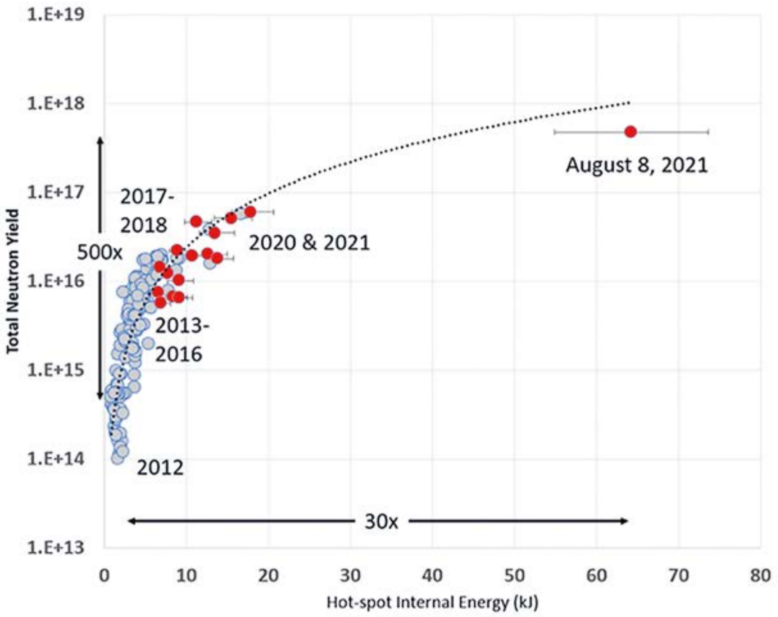
[1] https://lasers.llnl.gov/news/hybrid-experiments-drive-nif-toward-ignition#anatomy

[2] A cavity whose walls are in radiative equilibrium with the radiant energy within the cavity.



▲ **FIG. 3:** Neutron yield as a function of the total hot-spot internal energy as obtained from recent measurements[1].

hot-spot, enabling additional fusion reactions and sustaining the propagation of thermonuclear burn out of a hot-spot that consumed approximately 2% of the compressed fuel. The small amount of burnt fuel indicates a potential of larger energy output that can be obtained, estimated to be up to 20 MJ with an overall energy gain of about 10, provided fuel confinement is appropriately increased, with a similar target design.

IMPROVING THE ENERGY YIELD

If the burn wave propagates out of the hot-spot into the surrounding compressed fuel a large amount of energy can be released with the yield Y given by:

$$Y \propto \varepsilon^{23/6} \frac{v_{imp}^{23/3}}{\alpha_{if}^{12/5}} S^{14/3},$$

where ε represents the efficiency of conversion of the capsule kinetic energy into internal energy of the compressed fuel at stagnation, v_{imp} is the implosion velocity of the capsule, α_{if} is the "adiabat", a measure of the in-flight fuel entropy, and S is the spatial scale of the implosion, namely the normalised initial radius of the fuel-ablator interface. The equation clearly shows how the yield is sensitive to the implosion velocity, to the spatial scale, and to how efficiently the kinetic energy is converted into internal energy at stagnation. Based on this scaling, different configurations have been designed and tested at NIF over the past decade. Experiments have increasingly shown that a number of manufacturing issues play a crucial role in the implosion performance. Among these parameters, the roughness of the capsule surface, the thickness of the membrane holding the capsule in the Hohlraum, the diameter of the filling tube and the density of gas fill in the Hohlraum, were found to have a profound effect on the outcome of the implosion. Progressive control of these parameters enabled scientists to achieve successive improvements in the target design that finally led in August 2021 to an extraordinary performance in terms of neutron yield.

Towards high gain ICF: direct drive

The main outcome of the NIF achievement is the demonstration of the validity of the ICF approach to achieve thermonuclear fusion in the laboratory. Future experiments will tell how to improve the performance further, increase the compression of the fuel, improve implosion efficiency and increase fusion energy yield. At the same time, the results enable the community to strengthen the path towards ICF schemes with higher potential gain, tackling the major sources of loss of efficiency to overcome current limitations. The main gain limitation of the indirect drive ICF scheme used at NIF is the inefficient delivery of input energy into the capsule, that requires the prior conversion of laser energy into X-rays in the Hohlraum to smoothly drive compression of the capsule. The situation may change significantly if this intermediate step could be removed as it happens in the case of ICF with *direct drive*, in which the capsule is illuminated directly by the laser light as in the original ICF scheme [1].

Direct drive was extensively explored in the past, showing limitations due to the onset of hydrodynamic instabilities and laser-induced instabilities responsible for a high level of laser light backscattering and pre-heating of the compressed capsule due to fast electron generation.

More recently, however, advanced ignition schemes for direct drive ICF were proposed with the aim of overcoming the stringent requirements on the compression uniformity and symmetry of the original direct drive scheme to achieve central hot-spot ignition. Among these schemes the *shock-ignition* scheme [4] foresees a 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 (Figure 4). The scheme is expected to achieve high gain with moderate laser energy [4], and is being considered for Inertial Fusion Energy (IFE) research along with other advanced ignition schemes like fast ignition or magnetised linear inertial fusion.

The path to IFE: a new European Infrastructure

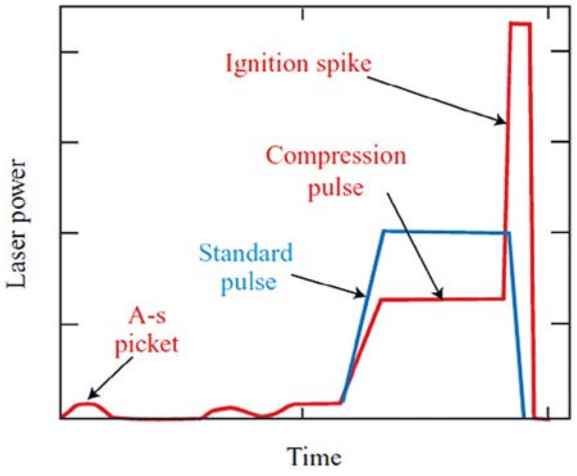
New energy sources that are both sustainable and free of CO_2 emission are required to respond to the current climate change crisis. Fusion energy is considered as the ultimate, long-term solution for energy supply and many complementary approaches are being pursued including magnetic and inertial confinement. The roadmap of magnetic fusion energy (MFE) has long been established with the International Thermonuclear Experimental Reactor (ITER) currently in construction in Cadarache (France) and other alternative smaller-scale approaches such as the stellarator

Wendelstein 7-X at the Max Planck Institute for Plasma Physics (Germany) or private endeavours like the Commonwealth Fusion Systems (USA). In contrast, an international roadmap for IFE has not yet been established, although IFE development programmes were started in several world regions, including USA, Japan and Europe.

The HiPER (High Power Laser Energy Research) infrastructure project (2006-2013) was included in the 2006 European Strategic Forum for Research Infrastructures (ESFRI) Roadmap and was aimed at exploring the science and technology of laser-driven fusion schemes, with a special focus on advanced ignition. Another equally important objective of HiPER was to build a sustainable, long-term, basic science programme in a wide range of associated fields and applications. HiPER allowed for the first time to tackle not only target ignition and burning but also reactor relevant issues like chamber design and materials under IFE conditions. The MJ scale energy yield demonstrated at NIF confirms that ICF is a viable solution for fusion energy and the scientific community is now strongly advocating [6] the establishment of a new IFE programme in Europe aimed at pursuing the original HiPER objectives and developing a roadmap to assess the feasibility of an IFE power plant based on burning of deuterium and tritium [HiPER+[3]].

An important mission of this initiative is to design and build a European intermediate-energy facility dedicated to laser fusion energy, which will scale up the many years of successful investigations carried out at several laser facilities in Europe. This scientific endeavour involves a fairly large community that is now supported for networking activities by the European research consortium EUROfusion and has fulfilled many important scientific milestones that give confidence in the ●●●

▼ **FIG. 4:** Laser power temporal evolution in the two advanced ignition direct-drive ICF approaches known as shock-ignition [4].



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[3] https://www.clpu.es/Laser_Fusion_HiPER

next stages to demonstrate high gain, direct drive fusion ignition. These next stages include scaled experiments at intermediate facilities, development high repetition rate laser and target technologies and materials, fusion ignition demonstration at megajoule facilities. Full-scale demonstration experiments require large laboratories of the scale of NIF or the Laser MegaJoule (LMJ) CEA, France. LMJ is currently in construction, although near completion, with ongoing precursor activity. Scaled experiments can be performed also at the Omega facility (Rochester, USA), which is the only academic installation capable of performing integrated implosion experiments; here the physics of direct-drive ICF has been investigated in depth at the energy level of 30 kJ.

A similar facility but based on the latest laser technology, possibly with a higher repetition rate, is needed by the scientific community to establish a science and technology IFE programme in Europe. High energy density science and direct-drive laser fusion could be studied there in coordination with the realization of several full-scale experiments at LMJ or NIF. This new facility will make it possible to investigate the needs and challenges of future high-repetition-rate, IFE configurations, including assessments of science-based technologies and materials for the target fabrication and reactor construction. In particular, similarly to MFE, the first wall of the vacuum chamber and blanket design for advanced reactors require dedicated experimental and modelling effort.

IMPROVING THE CAPSULE DESIGN

A representation of the progressive improvement in performance of the sequential experimental campaigns is clearly inferred considering the *figure of merit* of each shot based upon the areal density, ρR and the temperature, T of the imploded hot-spot:

$$(\rho R)^3 T^3 \sim E_{HS} P_{HS}^2,$$

expressed in terms of E_{HS}, the hot-spot internal energy and P_{HS}, the hot-spot pressure [2]. It is worth mentioning here that ρRT is the analogous of the triple product $n\tau T$ used in magnetic fusion, with n being the ion density of the plasma. Design changes include a larger capsule, a high-density carbon ablator, a low-density gas fill, and slightly larger Hohlraum. The larger capsule considerably increases the fraction of energy coupled to the capsule and to the hot-spot. To counteract the detrimental effects expected for this change of scale on the spherical symmetry of the compression, the laser energy across the different sets of laser beams was balanced using the Cross Beam Energy Transfer (CBET) occurring in the Hohlraum due to the presence of a low-density plasma. The upgrades led to the major advance in implosion performance and neutron yield increase up to 170 kJ in 2020. A further improvement was then introduced by slightly reducing the laser entrance holes of the Hohlraum and extending the laser pulse duration by a few hundred picoseconds to sustain the implosion velocity in the late stage and increase the stagnation pressure, thus transferring more energy in the hot-spot. These further modifications, along with an improved quality of the high-density carbon capsule shell and a reduced two-micron-diameter tube to fill the capsule with fuel, were successfully implemented and led to the extraordinary result of August 2021, with the achievement of up to 11 keV burning fuel temperature and the production of 4.8×10^{17} neutrons and alpha particles, for a total energy of 1.35 MJ.

In this context, the recent EU large investments in the Extreme Light Infrastructure have generated a strong involvement of the EU laser industry that is now prepared to respond to the challenges that the proposed IFE infrastructure is setting. The new laser technologies developed recently, including efficient diode pumping, high repetition rate and broad-band wavelength capabilities, are becoming key building blocks in several areas of high-power laser-based technologies involving manufacturing industry, healthcare, security, as well as in other large scientific infrastructures, as demonstrated by the growing number of dedicated installations, also across EU. These technologies are crucial to future IFE power plants, and the proposed installation will set a steep change in the pace of their development and readiness, further strengthening the leading role of EU laser and high-tech industry.

Conclusions

The achievement of megajoule energy yield at the NIF sets an historical milestone in Fusion Energy research that makes inertial fusion one of the very few viable approaches for future clean energy production. Europe has a unique opportunity to empower research in this field and the scientific community is prepared to engage in this journey.

Acknowledgements

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