INERTIAL CONFINEMENT FUSION: A PATH TO CARBON-FREE ENERGY?

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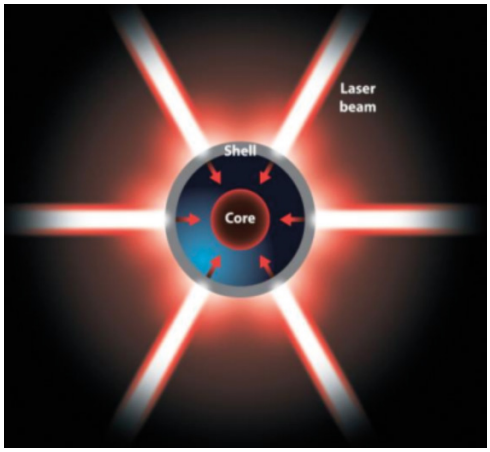

Scientists are trying to harness nuclear fusion reaction since the 1950s. Indeed, fusion of the two isotopes of hydrogen, Deuterium and Tritium ("DT"), generating an alpha particle and a neutron, can produce 337 MJ per mg of fuel, promising abundant, carbon-free energy. The scientific community is pursuing two approaches in this quest: magnetic confinement fusion ("MCF") and inertial confinement fusion ("ICF").

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If MCF has taken the major part of attention and budget in fusion for energy, with the ITER project and other research and private initiatives, ICF has taken a significant step on December 5th, 2022 by being the first to reach the long thought after "ignition point". On this day, the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in California generated 3.15 Megajoule (MJ) of nuclear energy by imploding a capsule filled with Deuterium and Tritium with 2.05 MJ of laser energy.

The principle of ICF (fig 1) is to irradiate a millimetre-scale spherical capsule filled with deuterium and tritium with very high power radiation during a few nanoseconds. The ablation of the outer surface of the capsule leads to compression of the DT fuel, leading to density and temperature (~ 100 millions K) sufficient to trigger fusion reactions. The alpha particles generated are then re-absorbed in the plasma, increasing further its temperature to trigger a large amount of fusion reaction that can consume a large fraction of the DT fuel.

Reaching this state of burning plasma necessitates extremely symmetric irradiation and very tight capsule tolerance. This has made the quest for ignition elusive until the NIF breakthrough, repeated five times since 2022, with energy output reaching 5.2 MJ for 2.2 MJ of invested laser energy, confirming the maturation of the inertial confinement fusion (ICF) science.

Those spectacular results are opening the door for finally making true the precept that fusion has always been "30 years away". Therefore, a number of public and private initiatives are now underway to take on the significant technological and engineering challenges that stay in the road between ignition at NIF and viable carbon-free ICF based power plant.

FROM IGNITION TO A FUSION POWER PLANT?

In an extremely simplistic way, a fusion power plant will follow the basic principle highlighted by the schematic of Fig 2. A capsule filled with about one mg of deuterium and Tritium is injected in a reaction chamber where it will be irradiated by multiple laser beams of megajoule energy. The implosion of the capsule can lead to

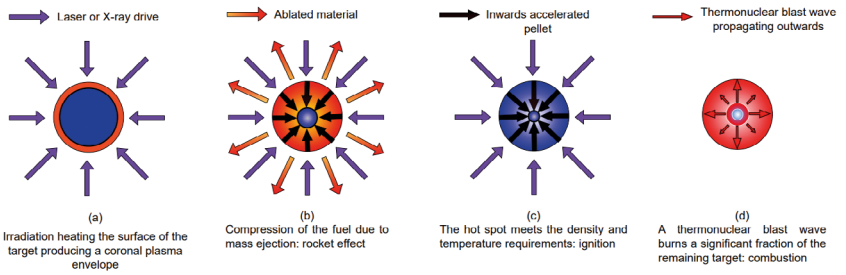


Figure 1. Principles of inertial confinement fusion (taken from Ref 3).

the combustion of up to 30% of the DT, leading to the release of more than 100 MJ. Repeating the process multiple times per second will result in Gigawatt average power generated mostly in the form of fast neutrons (14.3 MeV).

A lithium-based compound will absorb neutrons, providing two functions: convert the energy to heat and regenerate Tritium (whose supply is extremely scarce on earth). The conversion of heat to water vapour and electricity will then be very similar to a traditional power plant.

THE PATH TO LARGE GAIN

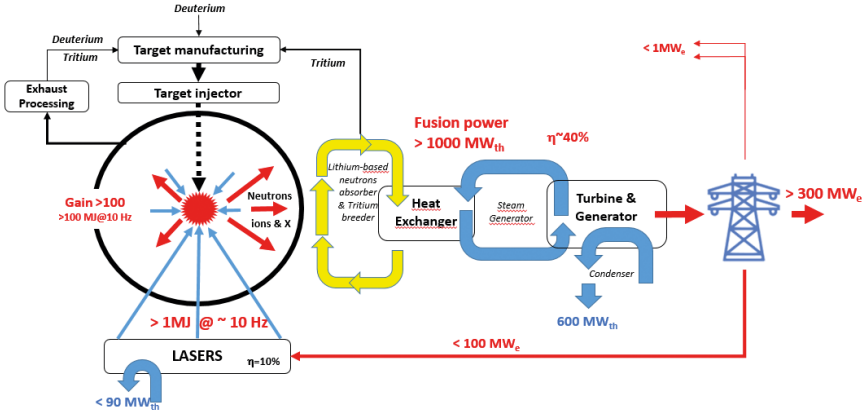
The gain of the reaction (ratio of fusion energy divided by laser energy) has to be large enough to compensate the energy required for the lasers and other sub-systems in the power plant. This is not the case in NIF where a gain of ~ 2.5 does not come close to compensate the laser efficiency far below 1%.

The experiments at NIF and its French equivalent the Laser Mega Joule ("LMJ") use the so-called indirect drive irradiation. In this case, X-ray radiation, generated by interaction of the main laser beams with the inner wall of a cylindrical cavity ("Holrhaum"), implodes the deuterium-tritium capsule. It benefits from the X-ray very short wavelength but has a poor efficiency, only a small fraction of the laser energy being coupled to the capsule.

Even if NIF expects gains of around 15 with indirect drive in a near future, direct drive, where the laser beams directly irradiate the capsule seems more promising to reach gains of 100 or more.

All potential ICF "recipes" face a major challenge: controlling the instabilities at work during the implosion. Hydrodynamic instabilities occur at the interface between two fluids moving in opposite direction (in case of ICF, the light and hot ablated matter against the heavier and cold capsule) or at different speeds (see Fig. 3). They will grow from any even minor non-uniformity in laser irradiation ("laser imprint") or capsule structure, stopping the compression from converging towards ignition conditions. ● ● ●

Figure 2. Simplified principle of an ICF power plant.



Laser-plasma instabilities ("LPI") exacerbate those non-uniformities and reduce efficient coupling of the lasers into the plasma. LPI include several non-linear processes occurring when a high-intensity laser interacts with a plasma: stimulated Brillouin scattering ("SBS"), stimulated Raman scattering ("SRS"), two-plasmon decay ("TPD"), cross beam energy transfer ("CBET"). Each one depends on specific laser parameters (intensity, wavelength, spectral bandwidth…) and plasma characteristics.

ADVANCED DIRECT DRIVE SCHEMES

To control instabilities, complex trade-offs are necessary but some schemes can offer realistic paths to high gain by decoupling the compression and ignition function. In shock ignition (Fig. 4), a first irradiation ramp over ~ 10 nanoseconds provides a more modest compression, followed by an ignition spark provided by a faster (~ 1 ns) laser pulse that creates a corresponding shock at the end of the compression. In **fast proton ignition**, a proton beam generated by a short laser pulse (<ps) laser provides the spark.

PROTON-BORON: ALTERNATE FUEL

The reaction of fusion of a proton with a nucleus of boron, yielding 3 alpha particles is an alternate path that poses the additional challenge of requiring much larger energies to initiate than the deuterium tritium reaction.

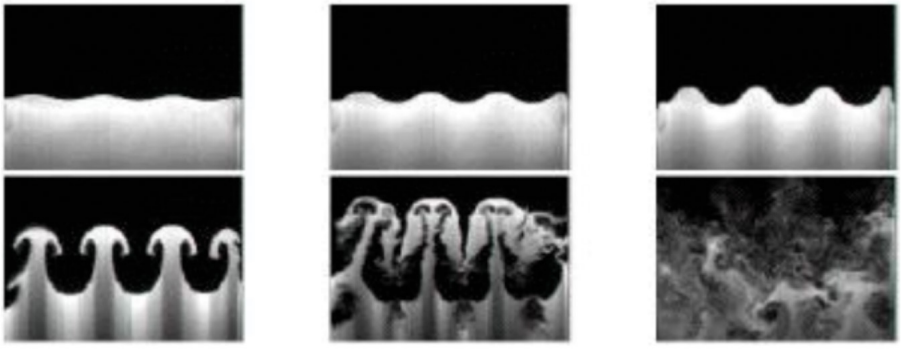
Marvel Fusion (Germany) proposes to use the interaction of ultra-fast and ultra-intense lasers (< 100 femtosecond pulse duration & Petawatt peak power) with nanostructures, creating extreme electric and magnetic fields to reach the necessary conditions for fusion without the need for compression.

THE LASERS

NIF and LMJ lasers represent logically the blueprint for fusion lasers but choosing and developing the right lasers for energy generation is a game of trade-off between the need of ICF physics and robust and economically viable solutions. Meeting the stringent requirements described in the previous paragraph requires several key decisions:

- **The choice of wavelength and spectral bandwidth:** the scaling of LPI instabilities and the ablation efficiency favour short wavelength like the third harmonic of Neodymium-glass laser ("3ω") at 351 nm selected for ICF facilities: NIF, LMJ and OMEGA (LLE, Rochester). On the other end, visible lasers (like second harmonic of Nd:glass at 527 nm) offer better efficiency and reduced risk of optical damage. Larger spectral bandwidth is preferred because it increases the threshold for LPI instabilities and reduces temporal coherence-induced non-uniformities but a compromise with efficiency is necessary. Excimer lasers that have the advantage of naturally emitting in deep Ultra-violet (248 nm or 193 nm) are another option but require complex technologies to scale up to very high energy.
- **Multi-beams irradiation and beam "smoothing":** reaching ignition requires a near-perfect spherical irradiation with typically 50 to 100 "meta beams" attacking the capsule at different incident angles. To minimize laser imprint, techniques like phase plates reduce coherence-induced speckle. Choosing the right "energy quantum" is a matter of providing the best uniformity but also finding an economic and reliability optimum. Consensus within the industry is to choose a reduced energy compared to NIF and LMJ for individual laser beams (10 kJ beamlet combined in 4 "quads") but will mean manipulate and control a very larger number of individual laser beams (probably more than 1000).
- **High repetition rate and high wall plug efficiency:** Flash lamp pumped Neodymium-glass lasers (NIF, LMJ, Rochester) are limited to shots every few hours with efficiencies well under 1%. Diode pumping is necessary and has shown capability to achieve 10 Hz at high energy with efficiency close to the 10% targeted but reduction in diode cost by one or two orders of magnitude is necessary.
- **Cheap and reliable:** IFE will happen only if it can reach a competitive electricity price (~ 100 € / MWh). This will need aggressive cost target, probably below 1000 € / Joules for laser capital cost and extremely low cost of operation & maintenance.

Figure 3. Hydrodynamic instabilities



FABRICATING CAPSULES

The state of the art capsule structure for ICF, exemplify by the one used for the NIF ignition experiment consists of a hollow shell of solid Deuterium-Tritium at cryogenic temperature (17°K), filled with DT gas. An external envelope serves both as radiation absorber for ablation and as containment for the ice DT. Fabricating those capsules is a gruelling task requiring lengthy injection and layering of the

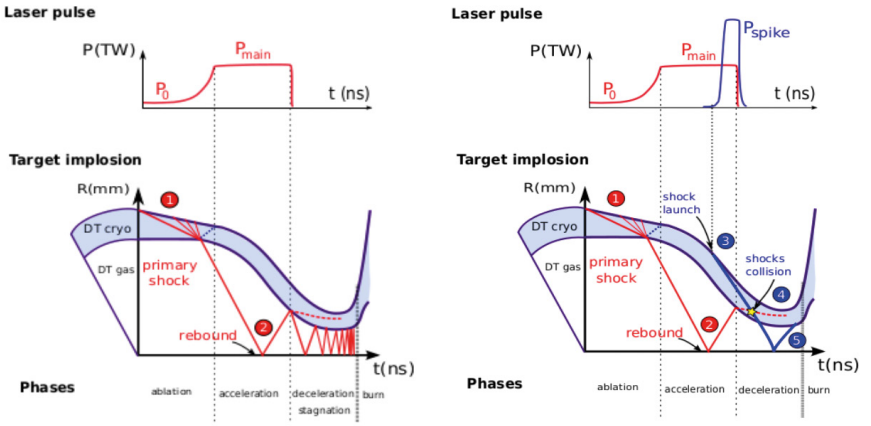


Figure 4. Hot spot ignition (left) and shock ignition (right) – Taken from Ref.[3]

DT ice and tedious dimension control to reach the extreme tolerance required.

Operating at 10 Hz, a fusion power plant will require close to a million capsules a day at a cost well below 1 €, forcing to develop new materials and manufacturing processes is necessary. Amongst the technology candidates, academia and industry consider the use of foams wetted by liquid DT. Work is underway at multiple research laboratories to characterize the interaction between lasers and foams to validate this approach.

If producing cheap ICF compatible capsules is a challenge, so is injecting them multiple times per second in the reaction chamber with synchronisation and position control to meet the laser beams at the right time and the right place.

ABSORBING THE ENERGY AND CLOSING THE TRITIUM CYCLE

Generating Gigawatt level of power is tough, absorbing this power and converting it to heat comes with its own challenges. Inertial confinement shares similar needs with magnetic confinement, creating opportunities for mutualizing the R&D.

In a first architecture, the inner solid wall ("first wall") of the reaction chamber absorbs the ions and charged particles (that can represent 25% of the total power). Tritium breeder modules ("TBM") absorbs the neutrons downstream of the first wall. Magnetic confinement research projects such as ITER consider multiple TBM technologies: Lithium based liquid (LiPb for exemple) or salt absorbing the neutrons and serving as heat carrying fluid or solid lithium based ceramic and in this case, heat exchange is ensured by gas or liquid.

In a second type of architecture, a plasma facing Lithium based liquid wall (for exemple FLiBe or Li-H) absorbs the reaction products inside the reaction chamber. This approach proposed by the project HYLIFE (Fig. 5) for ICF and selected by several companies (such as Xcimer energy in ICF, and Renaissance fusion in MCF) reduces stress on the chamber solid wall but necessitates complex engineering to control the liquid Lithium flow.

Closing efficiently the fuel cycle is critical: Tritium supply is scarce! ICF will be viable only in a self-sustained closed loop operation ensures Tritium self-sufficiency. Tritium breeding must have an efficiency larger than one (meaning that each neutron generates in average more than one Tritium) to account for losses or diffusion, necessitating a neutron multiplying scheme by adding more species for example Pb or Be. Tritium processing including purification and isotopic separation as well as capsules production will need to have a cycle time fast enough to limit the Tritium inventory to the minimum necessary for cost and safety reason (Tritium is radioactive, with a half-life of 12 years).

Intense activities are underway at research institutions for example under the ITER consortium to develop ● ● ●

THE NEED FOR DEDICATED DIRECT DRIVE INSTALLATION

ICF progress is limited today by the availability of dedicated laser installations. The NIF and LMJ are the only accessible MegaJoule class facilities and they suffer from two basic limitations:

- **Scarce shot opportunities: they are limited to around 300 shots per year and the majority of their access is dedicated to defence: if the NIF ignition needed 12 years of efforts, less than 200 shots were fired towards the goal over this period.**
- **Their polar irradiation geometry does not support fully symmetric direct drive experiment.**

On the other end, the OMEGA installation at LLE in Rochester is fully equipped for direct drive but laser energy is limited to 30 kJ. A lot of experiments and models are trying to scale results to high gain but uncertainties in the accuracy of this scaling remain.
IFE success will undoubtedly require at least one facility dedicated to R&D that can demonstrate high gain approach at a level that will enable subsequent scaling to power plant levels. This must be a priority and it will require very strong public-private partnerships.

concepts of breeding technologies, while companies and consortium such as Fusion Fuel Cycle Inc., (Canada) are developing Tritium purification capabilities.

A BURGEONING ECOSYSTEM

A large ecosystem of start-ups is emerging, gathering significant funding and forming strong academic partnerships.

Focused Energy (Germany & US) is pursuing direct drive proton fast ignition and is engaging in target and laser development in collaboration with university of Darmstadt. Marvel Fusion (Germany) is developing its concept of proton-Boron fusion based on interaction between ultra-intense lasers and nanostructures, with amongst others, collaboration with Colorado State University. Xcimer Energy (US) has chosen to develop ultra-high energy excimer lasers, beam combination and compression based on non-linear effects in gas, a dual-sided direct drive scheme and FliBe liquid wall for neutron capture and Tritium breeding. Longview fusion (US) is following the indirect drive, NIF-like path. Blue laser fusion (US) is proposing a disruptive approach by which Optical Enhancement Cavities convert the average power of quasi-continuous laser to high peak energy. HB11 (Australia) is also pursuing proton-boron fusion. GenF (Elancourt, France), is collaborating with CEA and CNRS laboratories (LULI & CELIA) with the support from French government and Thales.

Governments are now integrating inertial fusion in their energy policies with significant subsidies. US have launched a "bold decadal vision" with associated DOE funding. Germany has launched joint programs like "PriFusio" gathering startups (Marvel Fusion, Focused Energy), laser and optics companies (Trumpf, Laseroptik, Layertec, Schott) and laboratories (Fraunhofer ILT Achen, Laser Zentrum Hannover...). France selected the project Taranis (led by GenF with Thales, CEA and CNRS laboratories CELIA and LULI) in its H2030 "innovative nuclear reactor" funding program.

Laser manufacturers such as Thales, Amplitude and Trumpf as well as optics suppliers are all part of projects or industry-academic consortium to develop technology solutions towards IFE.

This rich private – public ecosystem is very diverse geographically but also in the broad coverage of all potential technical path: this raise expectations that it will collectively achieve a thorough pathfinding to identify the right combination of technologies to make energy generated by inertial fusion a reality.

CONCLUSION

The NIF results are finally validating the physics of inertial confinement, opening a different phase of the road to energy production. In this phase, the very complex challenge of the ICF physics is broken down into a set of engineering problems, albeit formidable ones but each one with potential solutions that are being worked on by a growing number of private and public actors. Rigorous system engineering is needed in parallel with those technology development efforts to find the optimum trade-offs that could lead to technically and economically viable IFE solutions by the mid-century.

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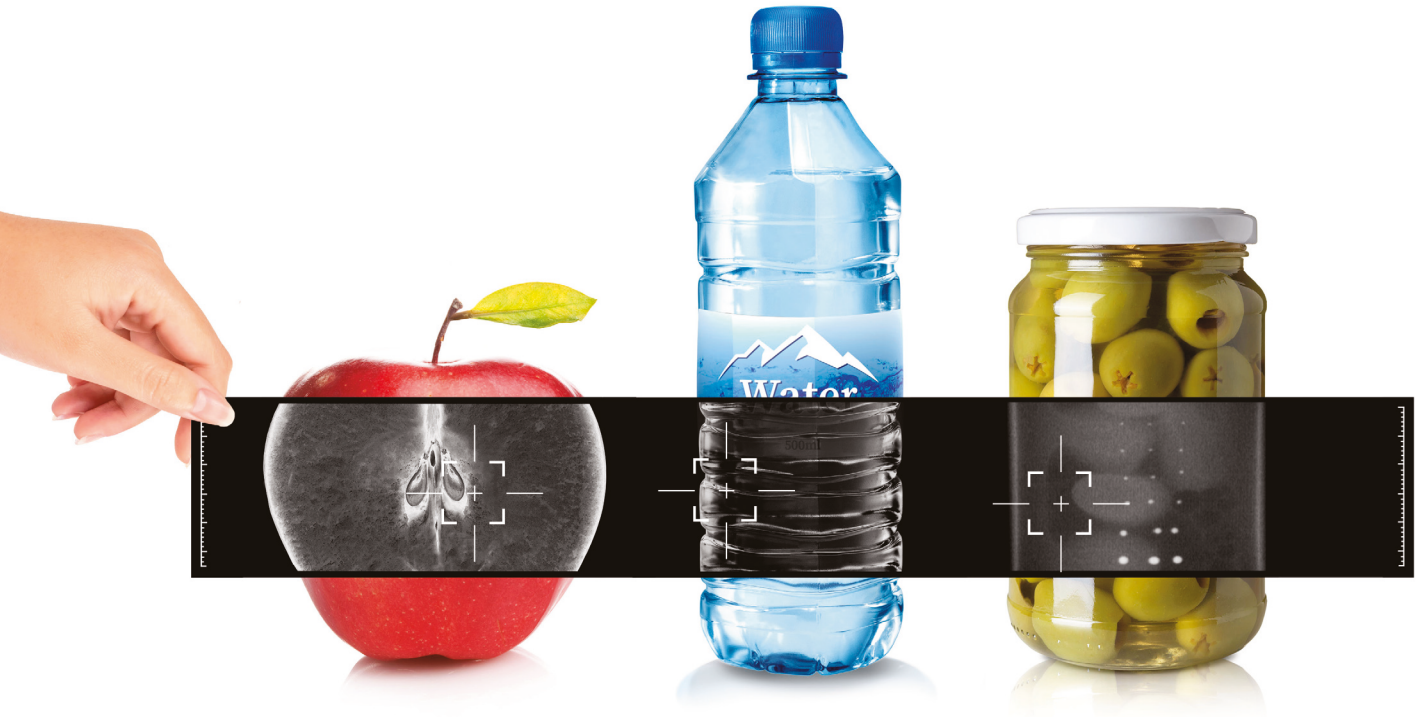
X-ray Inspection at High Speed



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