Nuclear fusion: how scientists can turn latest breakthrough into a new clean power source

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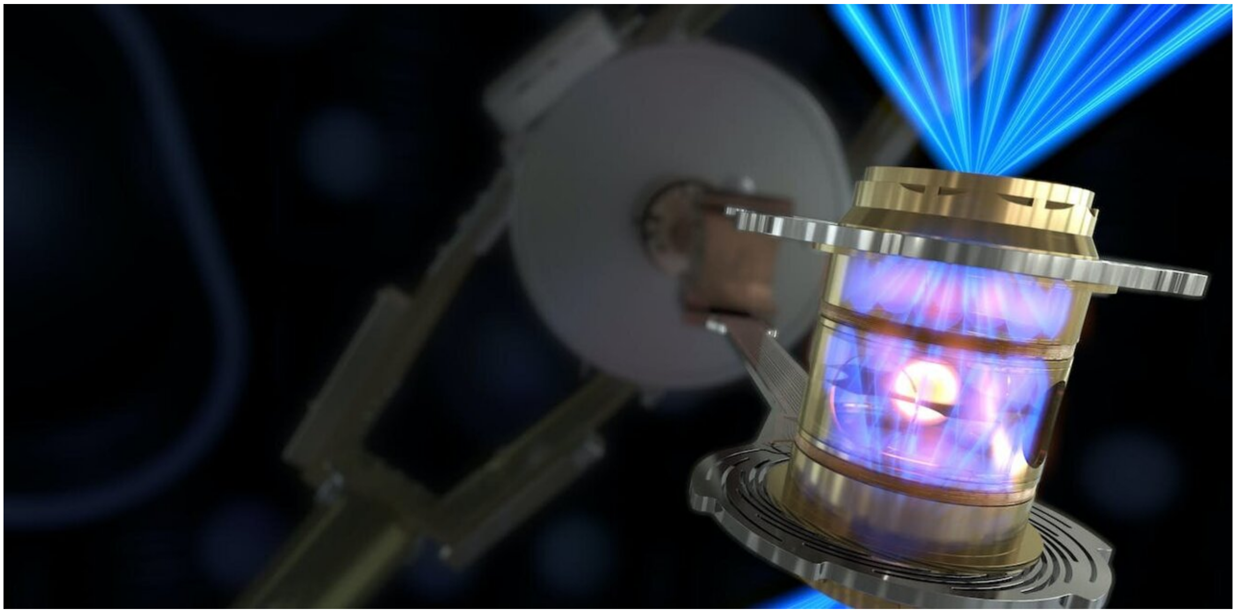

Laser energy being converted into X-rays inside a box, which compress a fuel capsule until it implodes. Credit: LLNL

Researchers in the US have finally fulfilled an objective that was set decades ago: the achievement of "ignition"—getting more energy out than you put in—using nuclear fusion.

The scientists at the Lawrence Livermore National Laboratory's National Ignition Facility (NIF), where the experiment took place, are no doubt both excited and relieved to finally fulfil the promise implied by the name of their facility. But how excited should the rest of us be? What does this really mean for the possibility of creating effectively unlimited amounts of clean energy, and what else needs to happen to achieve this?

While the fusion reactions released more energy that was put in to the target, this doesn't take into account the far greater quantities of energy needed to fire the laser that was used to drive the experiment. Also the burst of energy was not in the form of electricity, but a pulse of energetic particles. Harnessing those particles to produce electricity—and keeping a fusion reactor running constantly—will entail overcoming many hurdles.

Nevertheless, ignition is a remarkable achievement, and one which promises to stimulate interest in, and possibly also leverage funds for, tackling these further challenges.

The experiment: how it worked and what it achieved

Let's take a look at the details of exactly has been achieved. The researchers used a high-power laser to fire 2.05 million Joules of energy into a tiny target containing fusion fuel. This forced light atomic nuclei in the fuel together to create heavier nuclei—releasing 3.15 million Joules of energy in the process.

This corresponds to a gain of around 1.5 (2.05 x 1.5 = 3.1). It was a burst of energy so intense that, for a split second, burning fusion fuel produced ten thousand times more power than the combined output of every power station on Earth.

This is big science. The NIF building comprises not one but 192 individual laser beams, which bounce back-and-forth over a distance of more than a kilometre before they reach the target. The building which houses all of this tech is ten storeys high and the size of three (American) football pitches laid side by side.

Research into fusion falls into two main strands: laser driven fusion and magnetic confinement fusion. Magnetic confinement involves levitating fusion fuel in the form of a plasma (charged gas) using a large magnetic field.

Laser-driven fusion instead involves imploding tiny capsules of fusion fuel to incredibly high densities, at which point the burn will proceed so rapidly that significant energy can be released before the fuel has had chance to fly apart.

In both cases, the fuel must be raised to temperatures of tens of millions of degrees Celsius to start it burning. It is this requirement, more than any other, that makes fusion so difficult to achieve.

Laser-driven fusion still poses major challenges

Laser fusion is a pulsed technology, and a huge hurdle is the so-called laser repetition rate. Energy is released in intense bursts lasting much less than a billionth of a second, which must be repeated a few times every second to produce an average power output comparable to modern fossil-fuel based power stations.

The NIF laser by these standards is far too slow. It can be fired only twice a day. But NIF's goal was to demonstrate that ignition is possible on a single-shot basis, not to mimic the requirements of an actual power station.

Another reason that ignition took so long is that it is not NIF's only mission—it also supports the US nuclear weapons programme.

The physics of laser-driven fusion is so complex and multifaceted that computer simulations of it often take more time than actual experiments. Early on, modellers were more often learning from the experiments rather than telling the experimenters what to do next. An increasing closeness between model prediction and experimental outcome has underpinned the recent success at NIF and bodes well for future improvements in target design.

In the next few months, modellers and experimenters will need to show that the result can be reproduced—achieved again—something that has proven difficult in the past.

There are a number of other challenges to be tackled too. Considerable work has been done on designing and constructing lasers that can fire high energy pulses many times a second.

Another major limitation is that the NIF laser requires 300 million Joules of electrical input to provide two million Joules of laser light output—less than 1% efficiency. So the target would have to produce an unfeasibly large gain in order to produce more energy than went into powering the laser used in this instance.

However, the NIF laser is based on technologies that hark back to the 1980s. It uses flash lamps and amplifiers made from slabs of glass doped with the rare-earth element neodymium.

Modern high-power lasers using semiconductor technology can do far better, reaching around 20% efficiency. Given that laser-driven fusion targets are expected to be able to produce gains in excess of 100 when working optimally, using modern lasers would produce significant net energy output.

Building a working reactor is still some way off

Another challenge for laser-driven fusion is bringing down the cost of the targets. The manpower involved in making the NIF targets means that each one costs as much as a brand new car.

A new target is required every time the laser fires. For actual power production, this would mean a new one several times a second. The targets used on NIF also rely on a technique known as "indirect drive" in which the target first converts the laser energy into X-rays that then implode the fusion fuel capsule inside the target. This adds both complexity and cost.

Many scientists consider that the way forward for laser-driven fusion energy would involve "direct drive" ignition. Here, the laser directly illuminates a simple, spherical fuel capsule. This approach to ignition has, however, yet to be demonstrated.

NIF's fuel (deuterium and tritium) gives out much of its energy in the form of high-energy neutrons (particles which make up the atomic nucleus along with protons). The neutrons interact with the materials in the reactor vessel, changing their composition and microscopic structure.

This could pose serious challenges for optical components that must transmit or reflect laser light efficiently. Some scientists consider driving similar physics by alternative means, perhaps using pulsed electrical power directly, or focused beams of ions (charged atoms).

Magnetic confinement fusion research leads the way in many areas related to constructing a power reactor. It has had to tackle many of the same problems in order to design and build the ITER facility, which also aims to produce gain and is nearing completion in the south of France. Scientists and engineers from the two strands of research collaborate on aspects related to reactor construction which are common to both fields.

Fusion power has, for decades, seemed to be a prize that remains forever just out of reach. Though significant challenges remain, as researchers are now actively working on improving laser technology and reactor design, breakthroughs will inevitably lead to further progress towards nuclear fusion based power plants. Some researchers working on fusion are now sensing that they might see fusion providing energy to the grid within their own lifetimes.

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