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Self-heating plasmas offer hope for energy from fusion

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Many of the world's current energy sources are both unsustainable and harmful to the environment, so the idea that a relatively safe fuel is abundant in seawater will come as welcome news to many. But the energy is released in the process of nuclear fusion, in which two atomic nuclei combine to form a heavier nucleus — a difficult scientific and engineering feat to achieve, with many unanswered questions. Writing in *Nature*, Zylstra *et al.* [1] answer one such question by showing that, in the laser-driven approach to fusion, in which a plasma is compressed and heated, the plasma can be further heated by the fusion reactions themselves — a key requirement for self-sustaining fusion energy. Companion papers from the same group of researchers, by Kritcher *et al.* [2] in *Nature Physics* and Ross *et al.* [3] on the *arXiv* preprint server, detail the process of optimizing the experiment design.

Working at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in California, the team created a burning plasma using the hydrogen isotopes deuterium, which can be extracted from seawater, and tritium, which can be made in a reactor. In a burning plasma, the particles produced when the nuclei fuse take over as the main source of plasma heating. Zylstra *et al.* [1] showed that four experiments generated more than 100 kilojoules of energy. In one case, the authors were able to extract an impressive 170 kJ of energy from a millimetre-sized sphere containing less than one milligram of the hydrogen isotopes.

The experiment uses energy from 192 laser beams to quickly heat the interior of a hollow cylinder, generating X-rays (Fig. 1). This cavity, known as a hohlraum, contains a spherical capsule holding the deuterium–tritium fuel. The X-rays uniformly heat the outer regions of the capsule, making it expand rapidly and causing the fuel to accelerate inwards. Within ten-billionths of a second, the fuel and capsule are compressed to many thousandths of their volume, and temperatures reach 50 million kelvin at the centre. These combined effects cause the hydrogen isotopes to fuse, producing a neutron and an α-particle, which is the nucleus of a helium atom. The α-particles collide with the plasma, self-heating the fuel. Through careful analysis, Zylstra *et al.* showed definitively that their plasma was in a regime characterized by α-particle heating.

That the team achieved an output of fusion energy exceeding 100 kJ is not the only cause for excitement. In fact, although it is several times the energy injected into the imploding fuel, the output is actually rather modest. It is much less than the 1.9 MJ delivered to the hohlraum and the 400 MJ needed to operate the laser. Yet the precision and control of the experiments are extraordinary.

To achieve a burning plasma, the kinetic energy of the fuel moving towards the centre of the capsule must be converted to internal energy faster than any possible cooling, so that thermonuclear temperatures can be reached. The energetics are finely balanced — the challenge is to add enough kinetic energy to the imploding fuel to create a hotspot that is hot and massive enough to trigger and maintain thermonuclear reactions.

Before the compression commences, the capsule shell and fuel are nearly perfect concentric spheres. The capsule shell and fuel then implode together. The shell is heated by the X-rays and expands outwards while the fuel is pushed inwards, much like the fuel pushing a rocket forwards. As the implosion proceeds, more and more of the shell is ejected. When the implosion finally converges on the centre, only a fraction of the shell remains.

Any asymmetries or imperfections in these spherical shells are amplified when they implode. Asymmetries result in non-spherical compressions that reduce the efficiency of converting kinetic energy into heat. Imperfections can exacerbate cooling through thermal conduction and radiation losses by increasing the surface area of the hotspot at the centre of the compressed fuel, contaminating the fuel with shell material.

As the hohlraum heats up, its wall begins to expand, and this can make it difficult for the laser beams to penetrate its inner regions, causing asymmetries. To mitigate this effect, the hohlraum can be filled with gas to slow the wall expansion. However, the gas leads to instabilities that result in the laser beams scattering and carrying energy back out of the hohlraum. This, in turn, reduces the hohlraum temperature, disrupting the radiation symmetry and exciting problematic energetic electrons.

Researchers have previously overcome this problem by reducing the density of the gas in the hohlraum. But the hohlraum wall expands more quickly when the gas density is lower, so a faster implosion is required, which, in turn, means that more power is needed. The team’s solution to this particular problem is a feat of material and capsule engineering: a precision capsule shell made from polished polycrystalline diamond. The high-density material leads to better X-ray absorption, and requires shorter laser pulses and a thinner shell. As a result, the same size of capsule can hold a larger volume of fuel, which makes it more efficient in forming a central hotspot than capsules made from other materials [4].

Zylstra *et al.* used two strategies to optimize their experimental design. The first involved shifting the wavelength of the laser beams with the help of a photonic structure created in the plasma at the entrance to the hohlraum where the laser beams crossed, an established symmetry-tuning technique [5]. This effectively transferred energy from the laser beams focusing near the hohlraum entrance to those focusing in the interior. This energy transfer kept the hohlraum interior hot and the radiation field on the capsule uniform, thereby enabling a high-speed, symmetrical compression and resulting in efficient conversion of kinetic energy to heat.

Two of the experiments used a second strategy of changing the hohlraum from a simple cylinder to a dumb-bell shape. Having a radius slightly wider close to the laser entrance lessens the impact of hohlraum-wall expansion on the passage of the laser beams through the hohlraum. This reduces the wavelength shift needed to maintain the hohlraum temperature and radiation symmetry [6]. In the two companion papers, Kritcher *et al.* used computational models to investigate these two strategies, and Ross *et al.* detailed the thorough experimental testing of the optimized design.

The authors are confident that further improvements in performance will result in an ignited plasma, in which thermonuclear output power exceeds all loss mechanisms. And, in fact, they have already achieved this: in August last year, the NIF team announced an ignited deuterium–tritium plasma with a yield of 1.3 MJ and a gain of 0.7 (the gain represents the ratio of output energy to input laser energy). At present, the burning plasma is confined to the gaseous hot region at the centre of the fuel, and thus much higher gains will be required to convert the cooler fuel surrounding this hotspot into a burning plasma as well.

The achievements reported in the three papers advance the physics of burning and self-heating plasmas, enabling a whole range of scientific studies. Some of these pursuits will be key to national security, because the NIF is funded as part of the US programme to improve understanding of nuclear weapons and extreme environments (see *Nature* **597**, 163–164; 2021). It remains unclear whether this research will lead to a viable future power source. But the goal of developing a fuel that mitigates the dangers of climate change, while enabling us all to enjoy the benefits of electricity, is clearly worth pursuing.

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Figure 1 | Obtaining a self-heating plasma. Zylstra *et al.* [1] demonstrated that a fusion reaction can self-heat the plasma in which it occurs. **a**, The team's apparatus comprises 192 lasers that heat the interior of a hollow cylinder, known as a hohlraum, which holds a spherical capsule containing a plasma of the hydrogen isotopes deuterium and tritium. Laser power is absorbed by the hohlraum walls on impact. The heated walls radiate X-rays (not shown), which compress the plasma inwards, but this compression can be asymmetric, leading to energy losses. **b**, Through simulations [2] and experiments [3], the team optimized the set-up, introducing a photonic structure (not shown) at the hohlraum entrance to transfer laser power to the beams close to the interior, and altering the shape of the hohlraum. These improvements increased the symmetry of the compressed plasma, resulting in an energy increase. (Adapted from Fig. 1a of ref. [2].)