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Alternatives to tokamaks: a faster-better-cheaper route to fusion energy?

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The use of thermonuclear fusion as a source for energy generation has been a goal of plasma physics for more than six decades. Its advantages are many: easy access to fuel and virtually unlimited supply; no production of greenhouse gases; and little radioactive waste produced. But heating fuel to the high temperature necessary for fusion—at least 100 million degrees Celsius—and containing it at that level has proved to be a difficult challenge. The ring-shaped magnetic confinement of tokamaks, which emerged in the 1960s, was quickly identified as the most promising approach and remains so today although a practical commercial reactor remains decades away. While tokamaks have rightly won most fusion research funding, other approaches have also been pursued at a lower level. Some, such as inertial confinement fusion, have emerged from nuclear weapons programs and others from academic efforts. A few have been spun out into start-up companies funded by venture capital and wealthy individuals. Although alternative approaches are less well studied, their proponents argue that they could provide a smaller, cheaper, and faster route to fusion energy production. This article will survey some of the current efforts and where they stand.

This article is part of a discussion meeting issue 'Fusion energy using tokamaks: can development be accelerated?'.

1. Introduction

At the most basic level, a fusion reactor requires fusion fuel—in most cases an equal mixture of the hydrogen isotopes deuterium and tritium—to be heated so that it first ionizes, producing a plasma of electrons and ions, and then, at a much higher temperature, for the ions to collide together with such force that they overcome their mutual repulsion and fuse. This nuclear reaction produces a large amount of energy, much more than was put in to achieve it, so, in theory, the excess can be harvested and used to generate electricity. But the temperature required to achieve the reaction is such that the plasma must be prevented as much as possible from touching the walls of its containment vessel to avoid melting or otherwise damaging it.

The key parameters for reaching fusion ignition—a self-sustaining reaction that produces excess heat—are temperature (T), the number of ions per unit volume, or number density (n), and a quantity known as the confinement time, which measures how well energy is contained in the system (τ_E). Theorists have calculated that the requirement for fusion ignition is encapsulated in a simple formula known originally as the Lawson criterion, after British physicist John D. Lawson [1], and later refined as the triple product:

$$nT\tau_E \geq 5 \times 10^{21}\,\mathrm{keV\,s/m^3}.$$

To achieve fusion, very high temperature is a necessity, but as can be seen from the high value of the triple product, one or both of the other two parameters—density and confinement time—must also be large.

Tokamaks have got the closest to reaching the required triple product, with the Joint European Torus in the United Kingdom reaching 20% in 1997 [2] and Japan's JT-60 reaching 30% the following year. The international ITER fusion reactor in France, currently under construction, may or may not reach ignition but in any event, it is expected to produce more energy than is put into the reaction. In practice, a working fusion power plant may operate somewhat short of ignition (producing excess heat but still requiring some heat input into the plasma) because that gives operators an additional lever for controlling the reaction.

Tokamaks are at one extreme of the various ways of satisfying the triple product. Although tokamaks achieve high temperature and long confinement time, the density of gas in the reactor is low, lower than the air we breathe. A related device, known as a stellarator (which is discussed elsewhere in this special issue), also confines plasma using magnets, but in a different arrangement. These too achieve long confinement times but again at low density. At another extreme—high density and short confinement time—reside the approaches known as inertial confinement fusion (ICF).

2. Inertial confinement fusion

ICF was first developed at Lawrence Livermore National Laboratory in California in the 1960s and 70s [3], and the laboratory remains at the forefront of the field [4]. Its National Ignition Facility (NIF) is home to the most energetic laser in the world and the 192 beams it produces are converged on a fusion fuel target that is imploded by the 2-megajoule laser pulse to reach high temperature and high density conditions [5].

The implosion process is complex and involves several stages. The fuel capsule, a plastic sphere containing the deuterium-tritium fuel frozen onto its inner surface, is about the size of a peppercorn and is positioned at the centre of a gold cylinder about a centimetre long called a hohlraum. The laser beams are shone in through two holes, one at either end of the hohlraum, so that the light falls on the inner wall of the cylinder, not on the capsule. The beams heat the hohlraum material to high temperature so that it emits x-rays and these shine on the surface of the capsule causing some of the plastic to explosively fly off the capsule and so driving the rest of the capsule wall and fuel inwards towards its centre at several hundred kilometres per second (figure 1).

If symmetry is maintained, the fuel will be compressed into a ball with a density one hundred times that of lead and a temperature of 50 million degrees. According to theory, under these conditions, a fusion burn should begin in a hotspot at the centre of this ball and then propagate outwards consuming all the fuel. This is aided by a process known as alpha-heating, where the

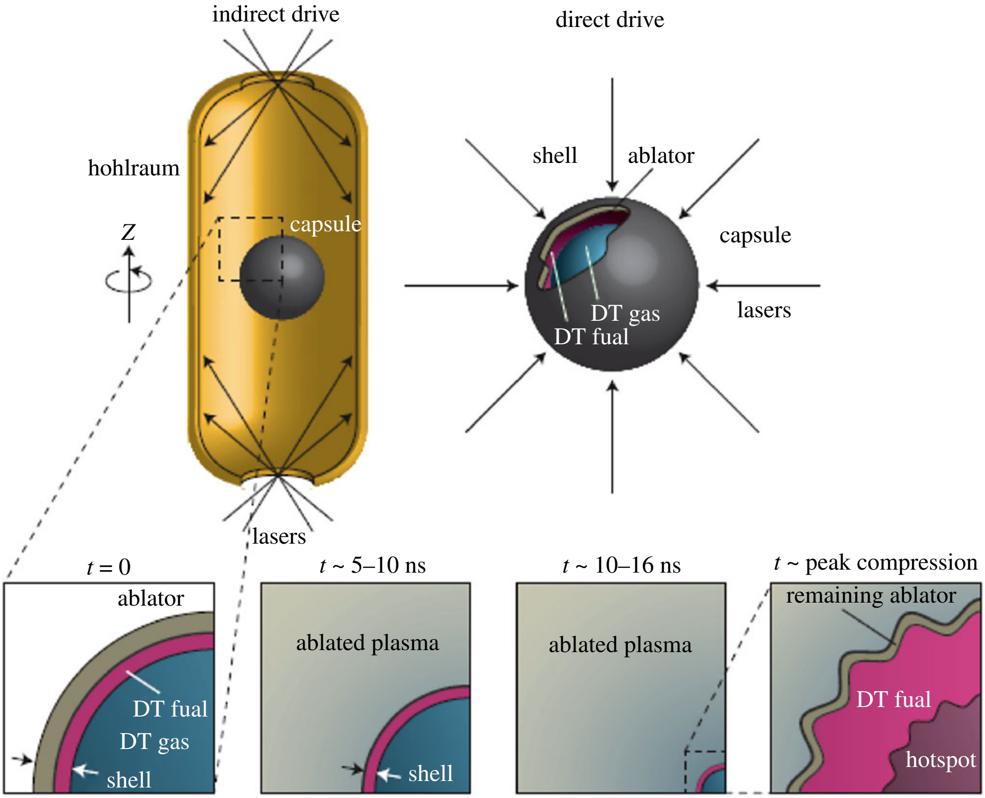

Figure 1. Schematics of indirect- and direct-drive ICF. Typical targets used in laser-driven ICF are indirectly driven (upper left) or directly driven (upper right). In either case, a spherical capsule is prepared at $t = 0$ with a layer of DT fuel on its inside surface. As the capsule surface absorbs energy and ablates, pressure accelerates the shell of remaining ablator and DT fuel inwards—an implosion. By the time the shell is at approximately one-fifth of its initial radius it is travelling at a speed of many hundreds of kilometres per second. By the time the implosion reaches minimum radius, a hotspot of DT has formed, surrounded by colder and denser DT fuel. (Credit: Omar Hurricane, Lawrence Livermore National Laboratory). (Online version in colour.)

helium nuclei—or alpha particles—that are the product of the fusion reaction fly off with high energy and, through collisions, heat the fuel to maintain the burn.

Following NIF's opening in 2009, researchers embarked on a 3-year campaign to achieve ignition but were unsuccessful [6] and remain so today. The computer simulations that the NIF team relied on to design their experiments predicted that they should be achieving ignition, so were of little use in figuring out what the problem was and how to solve it. Several years of experiment identified a number of problems: material blasted off the hohlraum wall was scattering the light of incoming laser beams, causing power to be lost; the fuel capsule was not imploding symmetrically, resulting in a doughnut shape rather than a tight ball; functional components in the hohlraum, such as the tube for inserting fuel and the membrane holding the capsule in place, were impacting on symmetry; and instabilities in the plasma during implosion caused turbulence at its edge, mixing shell material into the fuel and mixing cool outer fuel into the hotspot, reducing its temperature.

NIF researchers tried various approaches to get closer to ignition conditions. They modified the shape of the laser pulse which starts off at a low level and then peaks in power towards the end to start the burn [7]. By starting off at a slightly higher power to drive the implosion faster, they improved compression of the fuel but at the cost of reduced symmetry. Symmetry was improved by reducing the pressure of gas inside the hohlraum and using a thinner tube for the fuel. Changing the shell of the capsule from plastic to diamond has also improved performance and the team is experimenting with different sizes and shapes of hohlraum, such as a rugby ball shape.

These changes have produced a 40-fold improvement in the fusion yield—measured by the number of neutrons produced—since 2012 [8]. Omar Hurricane, chief scientist of the ICF program at Livermore says: ‘Our implosions are on the precipice of the ‘burning plasma’ regime.’ The term burning plasma refers to a situation where fusion reactions provide most or all of the heat required to maintain the burn. NIF can currently perform around one fusion shot per day. Researchers there calculate that if this approach was used to make a fusion power plant, it would need to carry out 10 shots per second to produce an economic power level.

An alternative form of ICF that avoids some of the complexities of NIF’s scheme is ‘direct drive’. This contrasts with NIF’s indirect drive approach by shining the laser beams directly onto the fuel capsule and dispensing with the hohlraum. This has the benefit of reducing the loss of power resulting from converting the ultraviolet beams into X-rays in the hohlraum, so more of the beam power reaches the capsule. A drawback is that any imperfections in the beam are translated directly to the capsule, potentially leading to an asymmetrical implosion. Hence beam quality is a major preoccupation of direct drive experiments.

The Laboratory for Laser Energetics (LLE) at the University of Rochester, New York, is the leading centre for this technique. Its Omega laser is not as high energy as NIF’s but LLE researchers have been working to refine the direct drive approach before moving their experiments to NIF. Just as at Livermore, the LLE team have been tweaking their available parameters in an effort to squeeze out improvements in performance. Recent experiments with a capsule that was larger in size but with walls of the same thickness led to increased implosion velocity and a tripling of the fusion yield [9]. Direct drive experiments are now taking place at NIF.

Other variations [10] on direct drive include shock ignition, in which the laser pulse ends with a very short, very intense spike in power to produce an inward-moving shockwave that will kick the plasma’s central hotspot into burning. This approach is being studied by LLE in collaboration with the University of Bordeaux in France and Rutherford Appleton Laboratory and the University of York in the U.K. Another variant, known as fast ignition, uses two lasers: one to compress the capsule in the same manner as direct drive, and a second to shine a single beam at the compressed fuel and, with very short, very high-powered pulse, set it alight. One benefit of this approach, which has been pioneered by the University of Osaka in Japan [11], is that the compressing laser does not need to be as powerful as NIF’s since it does not need to spark burning.

Several teams are also attempting to achieve ICF using not laser light but ion beams. The idea would be to accelerate two beams of heavy ions and then fire them into a hohlraum-like structure to initiate an implosion in much the same way NIF does. Most work right now is focused on developing accelerators able to produce ion pulses that are short enough and have high enough power [12]. One example is a linear accelerator called the Neutralized Drift Compression Experiment-II at Lawrence Berkeley Laboratory in California.

3. Magneto-inertial fusion

The two varieties of fusion examined so far, magnetic and inertial confinement, exist at extreme ends of the parameters permitted by the triple product, extremes that are complex and expensive to achieve. Other approaches explore the middle ground between these extremes at more moderate levels of confinement and density. Many groups are investigating this middle ground in the hope of finding approaches that are faster, simpler, and cheaper than the multi-billion-dollar facilities like ITER and NIF.

One midway approach is known as magneto-inertial fusion and a prototypical example is that being developed at Sandia National Laboratory in Albuquerque, New Mexico. Dubbed magnetized liner inertial fusion, or MagLIF, the Sandia approach uses a device called the

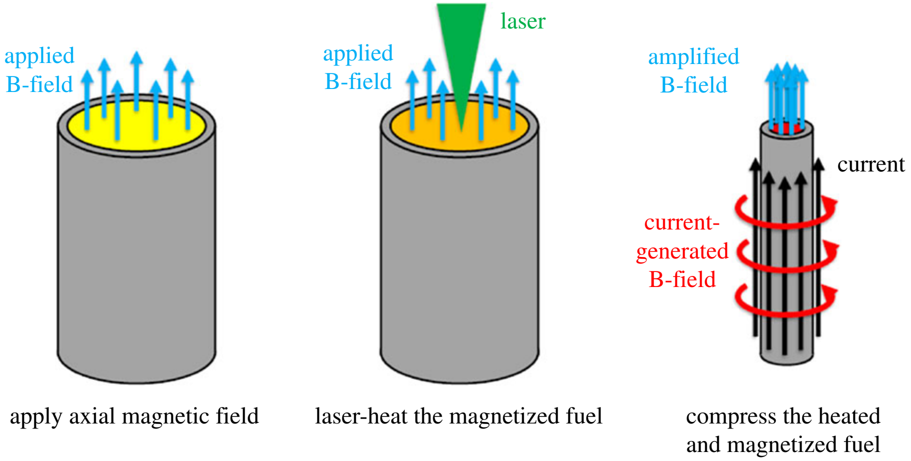

Figure 2. Schematic of magnetized liner inertial fusion (MagLIF). Deuterium-tritium fusion fuel is contained inside a cylindrical metal 'liner' and a magnetic field is applied to confine the plasma. A laser is used to heat the fuel. An intense electric current is passed along the wall of the liner, creating an encircling magnetic field that crushes the liner and its contents, also amplifying the applied magnetic field. (Credit: Kyle Peterson, Sandia National Laboratory). (Online version in colour.)

Z-machine which stores up a large amount of electric charge and can discharge current pulses in the range of tens of mega-amps. The fusion target is a small cylindrical metal can about 1 cm tall called a liner which is placed in the centre of the Z-machine. This is filled with fusion fuel and a magnetic field is applied along its length to hold the ionized fuel in the centre of the liner. Researchers then use a laser shone in through a window at one end to heat the plasma. Finally, the Z-machine discharges a current of 20 mega-amps along the walls of the liner and this generates an intense magnetic field encircling the liner which rapidly crushes it and its contents. In addition, the implosion boosts the applied magnetic field a thousand-fold (figure 2).

MagLIF is a relatively new technique and the researchers at Sandia are working to understand the physics of the processes involved [13]. But since beginning work in 2013 they have achieved a 2.5-fold improvement in yield. A power plant based on this approach, they calculate, would require one shot every 10 s. That slow rate is feasible because a MagLIF liner contains more fuel than a typical ICF capsule so produces more energy per shot.

Other approaches employ a plasma phenomenon called a compact toroid, in particular one known as a field-reversed configuration (FRC). This phenomenon, first observed in the 1950s, involves forming plasma into something akin to a rotating smoke ring. Plasma moving in this way generates its own magnetic field which acts to confine it, slowing down the dispersion of the plasma (figure 3). Although early FRCs lasted only a few millionths of a second, researchers were intrigued by them because they held the promise of providing a simple way to confine plasma. Although there has been much research on FRCs and other variations of compact toroid, none could be made to survive long enough to be useful for fusion energy. Now a new breed of start-up companies aiming to achieve faster/simpler/cheaper fusion has adopted FRCs for their approaches.

One example is General Fusion in Vancouver, Canada. The company, founded in 2002, has experimented to prove the feasibility of their approach and are now developing prototype-scale components in preparation for building a demonstration plant. The first part is a plasma injector that forms FRCs and fires them out at speed into the centre of the second part, a spherical reaction chamber. The chamber contains some liquid lithium which is spun up to coat the inner wall. This serves several purposes: it absorbs the high-energy neutrons produced in fusion reactions, preventing them from damaging the reactor structure; it absorbs the energy of the neutrons and

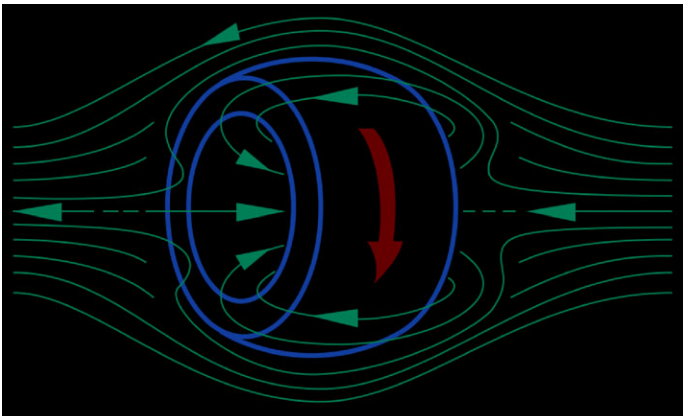

Figure 3. Field-reversed configuration. A ring of plasma (blue) which rotates (red arrow) creates a magnetic field (green) which helps to confine it. (Credit: Tokamac, Creative Commons).

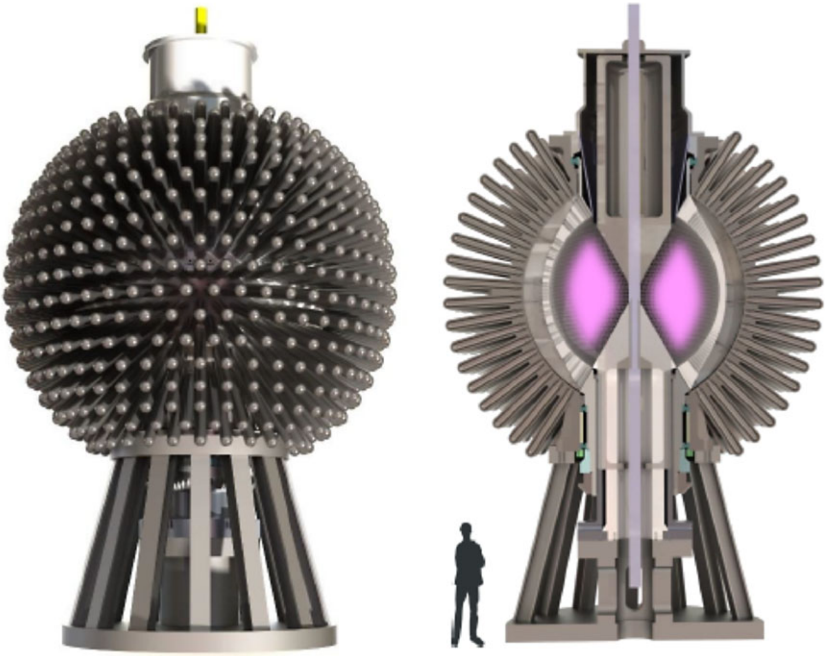

Figure 4. An artist's impression of General Fusion's demonstration reactor. (Credit: General Fusion). (Online version in colour.)

carries it out to be harvested and converted into electricity; and the neutrons convert some of the lithium into tritium, which can be collected and used as fuel for the reaction.

The third part of the system provides the compression which implodes the FRC once it reaches the centre of the chamber. It is comprised of up to 400 pneumatic pistons positioned all round the reaction chamber like spines on a sea urchin. These slam down in unison to produce a converging shock wave in the chamber centred on the FRC. The company is currently working to integrate these three components together into a demonstration reactor [14]. This will be able to perform around one shot per day but a working power plant would need to perform one per second (figure 4).

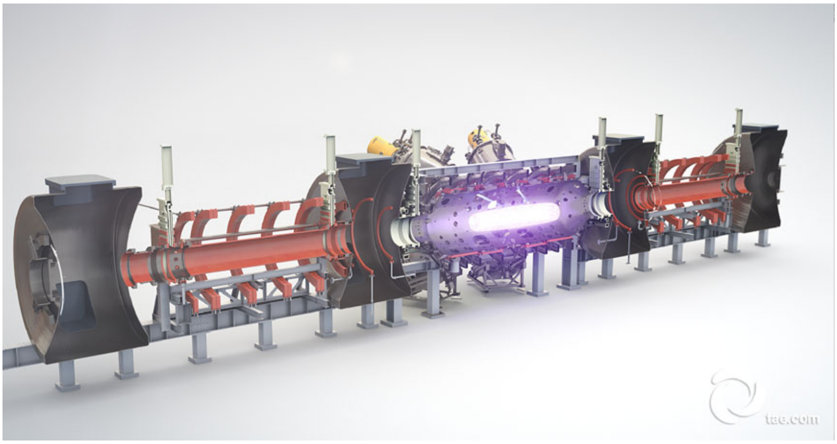

Figure 5. A cutaway of TAE Technologies' Norman device, showing a glowing field-reversed configuration sustained by neutral particle beams. (Credit: TAE Technologies). (Online version in colour.)

4. Other approaches

Another company, TAE Technologies (formerly known as Tri Alpha Energy) of Foothill Ranch in California, also uses FRCs but without the compression, instead attempting to prolong their life and so increase confinement time. The company's current device, named Norman after the company's co-founder Norman Rostoker who died in 2014, is the latest in a series of machines, each one increasing in scale and power. Norman is 25 m long with a plasma injector at each end. The injectors each fire an FRC inwards towards the centre at nearly 1 million kilometres per second. In a central reaction chamber, the two FRCs merge, converting their kinetic energy into heat, to form a cigar-shaped FRC about 3 m long and 40 cm across. The plasma is held there by magnetic fields while neutral particle beams are fired tangentially into the edge of the FRC to keep it spinning, stabilize it, and heat it (figure 5).

In 2016, TAE's previous machine, C-2U, produced FRCs lasting 5 milliseconds [15]. Norman, which has been operating since July 2017, has since produced FRCs lasting twice as long at a temperature of 3.5 million degrees [16]. By early 2019, the company hopes to have tripled that lifetime and increased temperature 10-fold, taking them close to the burning plasma regime. TAE is, however, not aiming for deuterium-tritium fusion but that of hydrogen and boron. This reaction has the benefit of only producing three helium nuclei (alpha particles) as reaction products and no neutrons. The high-energy neutrons generated by D-T fusion are hard to shield against and are damaging to both health and the reactor structure, making it radioactive. The alpha particles produced by proton-boron fusion can also be extracted magnetically from the reactor and their energy converted directly to electricity, removing the need for transporting heat, raising steam, and running turbines. The drawback of hydrogen-boron fusion is that it is harder to achieve and requires temperatures of billions of degrees.

The defence and aerospace company Lockheed Martin announced in 2014 that it is developing a compact fusion reactor which, it was claimed, could be transported on the back of a truck and could power ships or aeroplanes. Details are scarce, but it appears to be a form of magnetic trap in which plasma is confined and heated by neutral particle beams [17].

Another form of magnetic trap is the Polywell, currently championed by EMC2 of San Diego, California. First studied in the 1980s, a typical Polywell comprises six ring-shaped electromagnets, arranged as if on the six sides of a cube, all enclosed inside a vacuum chamber. The magnets produce a magnetic field that is zero at the centre of the cube but resists any charged particle trying to escape from the centre. To create the conditions for fusion, electrons are fired into the centre through the middle of the rings and become trapped there. When enough are collected in

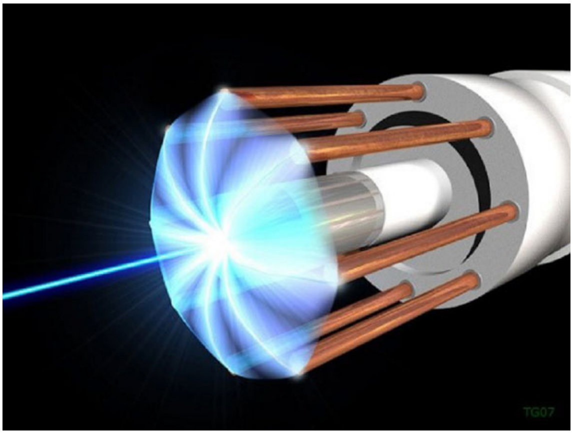

Figure 6. A dense plasma focus, showing filaments in the plasma linking the outer electrode (copper bars) with the inner cylindrical electrode and the particle beam produced by the central plasmoid. (Credit: Torulf Greek, Lawrenceville Plasma Physics).

the centre it creates a virtual electrode and a steep potential gradient between the centre and the outside. This gradient accelerates ions, which enter the cube via the corners, to a high enough speed for them to fuse with other accelerated ions when they meet and collide in the centre.

The problem with Polywells is that they are leaky traps with electrons able to escape via cusps in the magnetic field at the centres of the rings and the corners. Recent results from EMC2 suggest that with increased plasma pressure in the centre, the cusps become pinched off thus reducing leakage [18].

The final approach to be considered is the dense plasma focus (DPF) which has been studied since the 1960s. The company Lawrenceville Plasma Physics in Middlesex, New Jersey, has developed a DPF device comprised of two concentric cylindrical electrodes, with an outer diameter of 17 cm and around 30 cm long, all enclosed in a vacuum vessel filled with a gas of fusion fuel. When researchers put a pulse of electricity across the electrodes, the gas is ionized between the electrodes in a thin sheath of plasma made up of many tiny filaments. The sheath moves along to the end of the inner electrode where magnetic fields created by the current passing through the plasma twist the filaments into a tiny ball called a plasmoid. The magnetic fields collapse, and this generates two beams flowing from the plasmoid, electrons in one direction and ions in the other. The electrons heat the plasmoid to extreme temperatures, enough to spark fusion reactions (figure 6).

The plasmoid only lasts for 10 billionths of a second but achieves a plasma density close to that of a solid. Again, the energy of the ion beam produced can be harnessed directly into electricity. The company recently reported having achieved an ion temperature of nearly three billion degrees [19] so, like TAE, it is aiming for hydrogen-boron fusion.

5. Conclusion

This is not an exhaustive list of all the alternative fusion concepts being studied, but I hope it gives an idea of the breadth and diversity of the field. Just like with tokamaks, alternative fusion researchers have so far focused on the problems of reaching the necessary conditions for fusion reactions to produce excess heat. Once that is achieved, these approaches, like tokamaks, will have to overcome many engineering challenges before they can build a power-generating reactor, including how to extract heat and generate power, how to limit damage from neutron bombardment, and how to use those neutrons to breed tritium to use as fuel. Being smaller, faster, and cheaper does not necessarily make those problems easier.

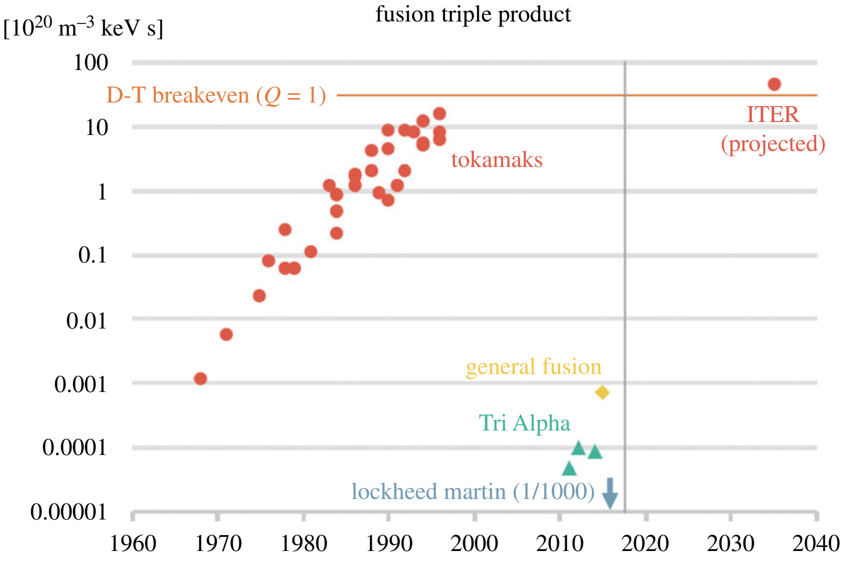

Figure 7. Evolution of fusion triple product. Tokamak researchers have worked long and hard to gradually improve performance to the point where devices are approaching energy gain. Alternative approaches have a long way to go but proponents believe they can accelerate development. (Points shown for Tri Alpha used deuterium as fuel, not the proton-boron fuel it hopes to use.) (Figure courtesy of Dan Brunner, Commonwealth Fusion Systems). (Online version in colour.)

As another dose of reality, figure 7 shows how tokamaks have improved their values of triple product over the past 50 years compared with several recent entrants to the field.

Their lowly position, some would argue, is due to lack of funding. ICF using lasers (and, to a lesser extent, MagLIF) has been generously funded by the U.S. National Nuclear Security Administration because the tiny thermonuclear explosions it creates are useful for nuclear weapons researchers. They provide some data against which to verify the computer models that ensure weapons are reliable and safe. Apart from those, other approaches receive virtually nothing from the U.S. or any other government. There was a glimmer of hope in 2015 when a U.S. Department of Energy initiative known as the Advanced Research Projects Agency – Energy (ARPA-E) began a program that supplied grants to a few alternative fusion studies. Those grants ended in 2018 and it is uncertain whether a new round of grants will be offered following the Trump administration's attempts to eliminate ARPA-E from the 2019 federal budget. The start-up companies are largely funded by a combination of venture capital, sovereign wealth funds, high net worth individuals, and crowdfunding. Some, including TAE and General Fusion, have managed to raise hundreds of millions of dollars in funding, but others have not been so fortunate.

Many in this field argue that concentrating so much money on one approach—tokamaks—while others are so poorly supported is not healthy. Fusion is too important for it to be limited to a single approach, they say; diversity reduces the risk.

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References

1. Lawson J. D. 1955 Some criteria for a power producing thermonuclear reactor. Report No.: GP/R 1807. Harwell, UK: Atomic Energy Research Establishment; 12 p.

2. Wesson J. 1999 The Science of JET. Report No.: JET–R(99)13. Culham, UK: JET Joint Undertaking; 189 p.
3. Velarde G, Carpintero-Santamaria N (eds). 2007 *Inertial confinement fusion: a historical approach by its pioneers*, 507 p. London, UK: Foxwell & Davies.
4. Betti R, Hurricane OA. 2016 Inertial-confinement fusion with lasers. *Nat. Phys.* **12**, 435–446. (doi:10.1038/NPHYS3736)
5. Clery D. 2009 Fusion's great bright hope. *Science* **324**, 326–330. (doi:10.1126/science.324.5925.326)
6. Clery D. 2012 Ignition facility misses goal, ponders new course. *Science* **337**, 1444–1445. (doi:10.1126/science.337.6101.1444)
7. Hurricane OA *et al.* 2014 Fuel gain exceeding unity in an inertially confined fusion implosion. *Nature* **506**, 343–348. (doi:10.1038/nature13008)
8. Le Pape S *et al.* 2018 Fusion energy output greater than the kinetic energy of an imploding shell at the National Ignition Facility. *Phys. Rev. Lett.* **120**, 245003. (doi:10.1103/PhysRevLett.120.245003)
9. Betti R. 2017 The one-dimensional cryogenic implosion campaign on OMEGA: modeling, experiments, and a statistical approach to predict and understand direct-drive implosions. In 59th Annual Meeting of the APS Division of Plasma Physics, Milwaukee, USA, 23–27 October 2017. Available from: http://meetings.aps.org/link/BAPS.2017.DPP.TI2.1
10. Clery D. 2015 Laser fusion, with a difference. *Science* **347**, 111–112. (doi:10.1126/science.347.6218.111)
11. Azechi H *et al.* 2013 Present status of fast ignition realization experiment and inertial fusion energy development. *Nucl. Fusion* **53**, 104021. (doi:10.1088/0029-5515/53/10/104021)
12. Bangerter RO *et al.* 2013 Accelerators for inertial fusion energy production. *Rev. Accel. Sci. Technol.* **6**, 85–116. (doi:10.1142/S1793626813300053)
13. Davies JR *et al.* 2017 Laser-driven magnetized liner inertial fusion. *Phys. Plasmas* **24**, 062701. (doi:10.1063/1.4984779)
14. O'Shea P, Laberge M, Donaldson M, Delage M. 2017 Magnetized target fusion at General Fusion: an overview. In 59th Annual Meeting of the APS Division of Plasma Physics, Milwaukee, USA, 23–27 October 2017. Available from: http://generalfusion.com/2017/10/magnetized-target-fusion-at-general-fusion-aps2017/
15. Gota H *et al.* 2017 Achievement of field-reversed configuration plasma sustainment via 10 MW neutral-beam injection on the C-2U device. *Nucl. Fusion* **57**, 116021. (doi:10.1088/1741-4326/aa7d7b)
16. Binderbauer M. 2018 On the path to clean fusion energy [seminar video]. Princeton Plasma Physics Laboratory, 17 March 2018. Available from: https://www.pppl.gov/events/science-saturday-path-clean-fusion-energy
17. McGuire T. 2015 The Lockheed Martin Compact Fusion Reactor [seminar video]. Princeton Plasma Physics Laboratory, 6 August 2015. Available from: https://www.pppl.gov/events/colloquium-lockheed-martin-compact-fusion-reactor
18. Park J *et al.* 2015 High-energy electron confinement in a magnetic cusp configuration. *Phys. Rev. X* **5**, 021024. (doi:10.1103/PhysRevX.5.021024)
19. Lerner EJ, Hassan SM, Karamitsos I, Von Roessel F. 2017 Confined ion energy >200 keV and increased fusion yield in a DPF with monolithic tungsten electrodes and pre-ionization. *Phys. Plasmas* **24**, 102708. (doi:10.1063/1.4989859)