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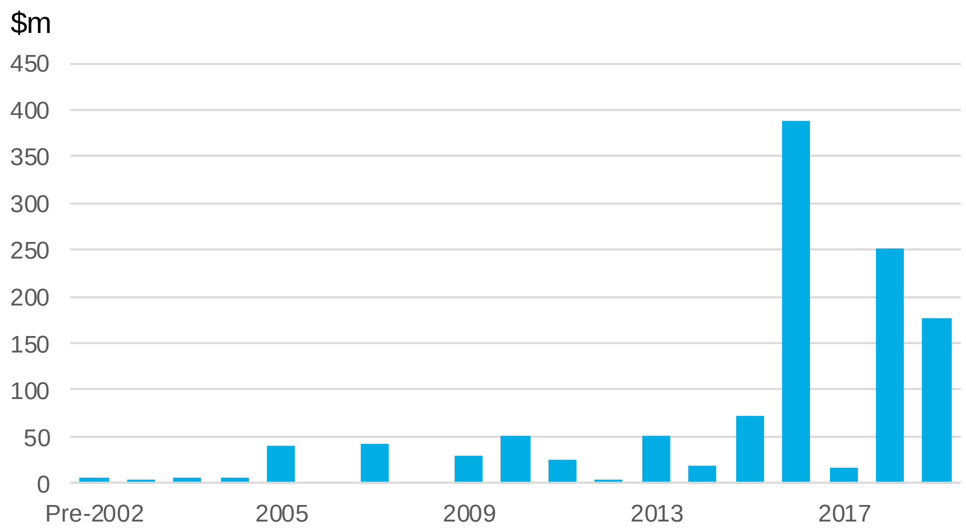
Chasing Disruption With the Promise of Fusion

Steadily and quietly over the past decade, a trickle of investment has flowed into a handful of start-ups focused on commercializing fusion technologies. Driving investor interest is the belief that advances in the fusion tools researchers and scientists use may deliver the promise of commercial fusion sooner and cheaper. Though competitive electricity remains years away, more than a dozen companies have raised nearly $1.2 billion. BloombergNEF explores the nuances of this potentially disruptive technology.

- The International Thermonuclear Experimental Reactor (ITER) project is a large, multinational scientific experiment to prove the viability of fusion by 2025-30. Alongside this government effort, more than a dozen start-ups are pursuing various leaner approaches to commercializing fusion.
- Fusion detractors have long argued that commercialization remains 20 years and $20 billion away. Recent advances in digitization, advanced materials, 3D printing and supercomputing may now enable a faster and cheaper path toward this clean energy solution.
- Increasing concerns over a changing climate and national and corporate commitments to decarbonize by mid-century have prompted widespread interest in investing in the space. Venture capitalists and billionaires including Jeff Bezos, Bill Gates, the late Paul Allen and Peter Thiel are doing so.

Figure 1: Annual investment in commercial fusion



Source: Company reports, SEC filings, BNEF estimates

Chris Gadomski

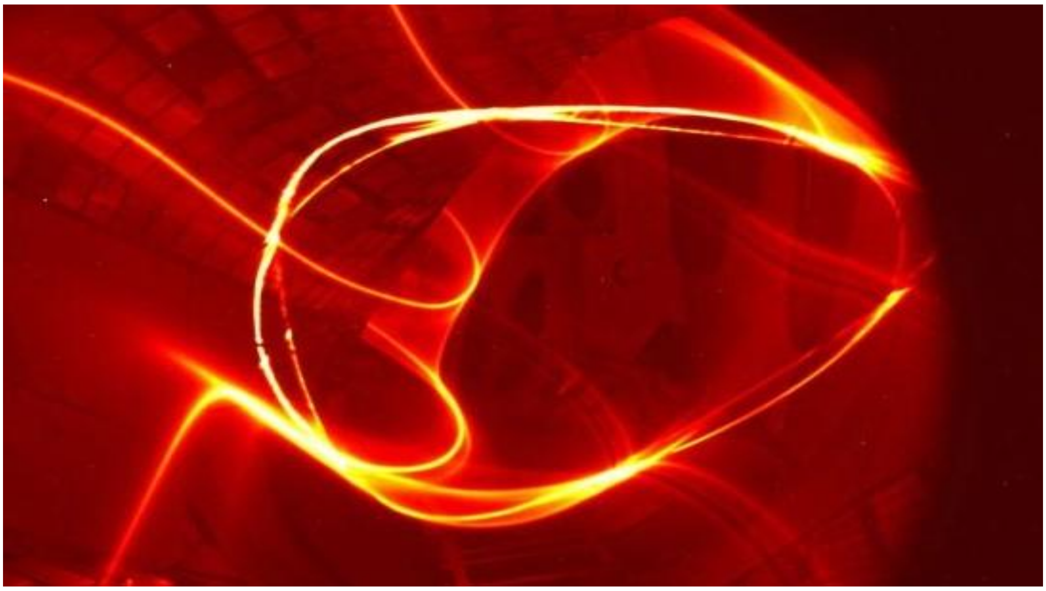
1. Fusion: the great potential disrupter

Fusion is the process that generates heat and releases light from our sun. Companies are now seeking ways to use that process here on Earth to generate energy – and have secured financing from some of the world's wealthiest investors.

In the fusion process, under intense pressure and super high temperatures in the core of the sun, hydrogen nuclei fuse together to produce heavier nuclei such as helium. The process releases huge amounts of energy as per Einstein's famous $E=mc^2$ equation. It is an undertaking that physicists and engineers are attempting to replicate in a variety of innovative fusion reactor designs.

Tokamaks[1] and stellarators[2] are the two most prevalent technologies used to produce fusion reactions. The ITER project under construction in France is the world's largest tokamak to test the fusing of hydrogen isotopes (deuterium-tritium) plasmas. The tokamak device generates a strong electrical current running in external coils to create a ring-shaped, twisted magnetic field to contain the plasma. More technically complex than tokamaks are stellarators which use twisting electromagnetic coils to confine plasma in helical magnetic fields in order to produce fusion reactions. Fusion company startups, however, are using a variety of different approaches to commercialize the technology.

Figure 2: Magnetic field surface in the Wendelstein 7-X stellarator



Source: Max Planck Institute for Plasma Physics Note: Camera image of magnetic field surfaces in the Wendelstein 7-X stellarator, the world's largest and most advanced, at the Max Planck Institute for Plasma Physics in Greifswald, Germany. This stellarator took 15 years to build at a cost of 370 million euro ($409).

[1] A tokomak is a doughnut-shaped apparatus for magnetically confining hot plasma for producing controlled fusion reactions.

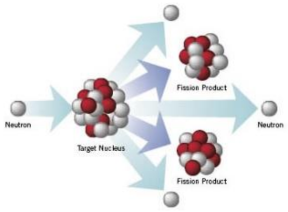
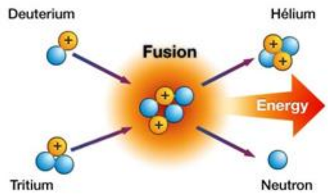
[2] A stellarator is a toroidal device using a series of external magnetic coils to support a controlled, sustained nuclear fusion reaction.

1.1. Fission vs. fusion

There are significant differences between fusion and fission as advocates of each are quick to point out. While fusion combines small nuclei, fission splits the nucleus of heavy atoms like uranium and plutonium. Both processes produce tremendous energy with which to create steam and make electricity. The world's 449 nuclear reactors, powered by fission, generate 11% of the globe's electricity.

Fusion developers argue the technology lacks the biggest headaches related to fission including safety, spent fuel, high costs, potential reactor meltdowns, and the proliferation of materials for nuclear weapons. Advanced fission developers on the other hand suggest that commercial fusion remains unproven and far in the future. Both processes result in less mass than the mass of the original nuclei resulting in tremendous energy release.

Table 1: Fission vs. fusion

	Fission	Fusion
Definition	Splitting of large nuclei into smaller ones	Combing of smaller nuclei into one larger nuclei
Where	Does not occur in nature	Process that powers the stars
Fuel	Uranium, plutonium, thorium	Deuterium from seawater, tritium, helium, boron
By-products	Long-lived radioactive particles	Few radioactive particles
Safety	Several significant failures	Inherently safe
Energy input	Takes little energy to split unstable fissile nuclei	Requires tremendous energy to fuse small nuclei
Energy output	Millions of times greater than chemical reactions	Three to four times greater than fission
Requirements	Critical mass and slow neutron to split large nuclei	Proximity of two nuclei under extreme pressure and heat
Diagram		

Source: BloombergNEF, Differencebetween.com, American Nuclear Society.

In fusion, no long-lived radioactive waste emerges with reactor components available for recycling after 100 years. Without fissile materials, there is no risk of meltdown or proliferation. A virtually unlimited source of deuterium from seawater is available to fuel fusion. Both fission and fusion do not omit greenhouse gases and fusion developers anticipate that innovative designs will deliver abundant clean electricity competitively.

One challenge for fusion innovators is getting enough plasma to stay very hot and long enough to fuse nuclei. In doing so fusion reactors will generate sufficient heat and energy to extend the reaction and generate electricity. Investors and developers are assessing what are the most viable fuels, what physical conditions achieve net energy gain, and how various approaches should be evaluated to distinguish between winners, longshots and losers.

2. What's changed for fusion?

Aside from the realization that climate change has driven nations, cities and companies to embrace carbon neutrality by mid-century, fusion may be nearer to commercialization because enabling technology and engineering has evolved far enough to attract investors with a healthy appetite for risk. The tools available to scientists and engineers from superconducting magnets to supercomputers, for example, have become more sophisticated and versatile. These include:

- **Magnets** are crucial for confining fusion plasma. Advances in magnet technology are leading to the design of smaller, more compact fusion reactors. The Massachusetts Institute of Technology, for example, has developed ways to make new magnets from novel superconductors that create much higher fields. High temperature superconducting material made of yttrium-barium-copper oxide (YBCO) will create a magnetic field four times as great and allow a tenfold increase in power output. This innovation, along with the deployment of high field permanent magnets, should reduce fusion reactor size and increase performance as well as facilitate operation at higher temperatures and with higher current densities.
- **Advanced materials** are being developed to endure the harsh environment within fusion reactors. With temperatures expected as high as 150 million degrees C, plasma-facing metallic alloys are necessary to respond to the challenges of controlled fusion. Experimental shielding blankets of steel alloys, for example, are infused with rare earths like beryllium to strengthen the walls of reactors subject to the disruptive flux of unstable plasmas.
- **3D Printing** and other advances in manufacturing will speed the development and production of complex twisting devices that comprise stellarators used to confine plasmas and other precise components for fusion reactors. This technology will shorten the time and reduce the cost of manufacturing fusion reactor components.
- **Advanced computing, modelling and digitization** support scientists developing optimal magnetic configurations which can be quite intricate for fusion devices like stellarators. Princeton University recently christened its Traverse supercomputer which will support fusion research at the Princeton Plasma Physics Laboratory (PPPL). The new petaflop supercomputer will empower researchers to prepare codes on exascale systems capable of a billion billion calculations per second. This computing boost will enable the research community to simulate and optimize the design of fusion reactors. Scientists are aiming to better control the density and temperature variations in fusion plasmas. Machine learning will lead to better models with which to control and contain plasma.

Collaboration with Google and using a U.S. DOE supercomputer program has boosted fusion developer TAE Technologies' data-processing resources. TAE has worked with Google since 2014 and in 2017 produced the Optometrist algorithm, a machine-learning tool to digest, noisy, continuous highly dimensional data. TAE attributed its rapid progress in part to its collaboration with Google on machine-learning simulations of plasma physics.

3. Growing pressure for deep decarbonization

In addition to the ITER project, there is growing public and private interest in fusion development that can contribute to a cost-effective zero-carbon grid by mid-century. The National Academy of Sciences' final report on the Committee on a Strategic Plan for U.S. Burning Plasma Research, recommends a national program to build a compact fusion pilot plant as a way to produce fusion electricity at the lowest capital cost. This pre-commercial learning research facility would operate for weeks at a time, produce tritium, and lead to the development of the first commercial fusion power systems. The committee recommended additional annual funding of $200 million beyond existing levels sustained for several decades.

The Fusion Energy Sciences Advisory Committee (FESAC) advises the office of Fusion Energy Sciences (FES) within the U.S. Department of Energy to identify and prioritize research to develop a fusion energy source. Congress last year increased FES' budget by nearly 50% over 2017 levels with $564 million for fiscal year 2019. Despite a FY20 budget request from the Trump Administration of $403 million (down 29%), a version of the budget under consideration in the Senate would boost spending by 1% while the House version sought a 22% increase over FY2019 levels. A final version of the budget with the actual spend level is expected to clear the Senate on December 19 and be signed into law before December 20 by President Trump.

The Advanced Research Projects Agency-Energy (ARPA-E) within the U.S. DOE focuses on supporting applied research that can overcome long-term, high-risk technology challenges that can lead to commercialization. Through its ALPHA portfolio it is funding research at a variety of fusion start-ups, universities and national laboratories. ARPA-E says the aspirational metrics for commercial fusion would be a cost of $5/W for a demonstration project with an overnight capital cost of less than $2 billion and an LCOE of $.075kWh.[3]

Private investors are responding as well with cumulative investment in fusion research in the U.S. and Europe exceeding $1.1 billion in venture and late stage financing for a variety of novel technological approaches. (Figure 1). ARPA-E cites $1.5 billion of publicly disclosed private funding worldwide since 2015.

With 84% of the world's energy produced by CO2 emitting sources, fusion entrepreneurs are aiming for a technological solution that will be able to respond to the world's increasing demand for energy without greenhouse emissions. Many of the world's billionaires are investing in fusion technology with a goal to create a new non-emitting energy source. They include:

- Jeff Bezos, CEO of Amazon, through Bezos Exhibitions, General Fusion
- Paul Allen, Microsoft Corp. co-founder, through Vulcan Capital, TAE Technologies, (formerly Tri-Alpha Energy)
- Bill Gates, Microsoft Corp. co-founder, through Breakthrough Energy Ventures (BEV), Commonwealth Fusion Systems. Other prominent investors of Breakthrough include Jack Ma of Alibaba Group, Richard Branson of Virgin Group, Michael Bloomberg[4], Jeff Bezos of Amazon, and Prince Alwaleed bin Talal of Alwaleedd Philanthropies
- Peter Thiel, PayPal founder, through Mithril Capital Management, Helion Energy

4. The latest innovations

Entrepreneurs, companies and investors in pursuit of fusion are developing a wide range of innovations with a goal to commercialize the technology as soon as the second half of the next decade.

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[3] ARPA-E Fusion-Energy Programs and Plans, Presentation to FESAC Oct 2, 2019

[4] Majority owner of Bloomberg LP

Table 2: Companies developing fusion reactors

Company	Technology	Source of funding	Investment (MM)	Notes
Commonwealth Fusion	Tokamak	Eni, BEV	$115	Spun off from MIT's Plasma Science and Fusion Center in 2014
CTFusion	Steady-state magnetic fusion	ARPA-E	$3	Spun off from the University of Washington in 2019. The company has received a $3 million ARPA-E award and is pursuing Series A funding.
First Light Fusion	Inertial confinement fusion	IP Group plc, Parkwalk Advisors Ltd, and angel investors	£23.7 ($30.5)	Spun out of Oxford University in 2011; expects to demonstrate net energy gain by 2024.
Fusion Energy Solutions of Hawaii	Velocity impact fusion	Self-funded	N/A	Seeking Series A funding
General Fusion	Magnetically-target fusion	Chrysalix Venture Capital, Bezos Expeditions, Braemar Energy Ventures, Cenovus Energy, Khazanah Nasional, Canadian Government, Temasek	$200	Founded in 2002, seeking support for the next phase of technology development, its $350M Fusion Demonstration Program. Completed $65 million Series E funding in December 2019.
Helion	Magneto-Inertial fusion	Mithril Capital, Capricorn Investment Group, Y Combinator	$12	Pursuing a small 50MW fusion reactor to produce electricity at $0.04kWhr
Hyperjet Fusion	Plasma jet driven magneto inertial fusion	Strong Atomics	$2	NASA, DOE, ARPA-E funded initial hyperjet research with $28MM
Lawrenceville Plasma Physics	Focus fusion	Abell Foundation, and crowd funding	$7	Pursuing a non-tokamak approach to fusion using a hydrogen-boron fuel.
Lockheed Martin	Magnetically-confined plasma	Corporate	$10*	Targeting compact fusion reactors for commercialization by 2025.
Princeton Fusion Systems	Field-reversed-configuration plasma	ARPA-E	$1.25	Working with the PPPL, the company is developing a small compact fusion device for power and space propulsion.
Proton Scientific	Inertial confinement	Not disclosed	$5	Pursuing $20m to scale device to the fusion ignition energy level
TAE Technologies	Self-confining plasma	Vulcan Capital, Goldman Sachs, Google	$700	The largest and best funded effort, the company's Norman machine is pursuing hydrogen-boron fusion.
Tokamak Energy	Spherical tokamak	Legal & General, Winton Capital	£50 ($65)	Company goal is a grid-connected power plant by 2030.
Zap Energy	Z-pinch fusion	ARPA-E, private investment	$13.7	ARPA-E award of $6.7m and a $7m private investment round expected to close in Q4 2019.

*Source: BloombergNEF, Company reports; Note: *BNEF estimate*

5. Research institutions and government funding

Besides commercial interest in fusion, several governments are continuing to support the private sector exploring the promise of this technology.

- ITER

The world's most ambitious fusion research effort is the International Thermonuclear Experimental Reactor (ITER) project where 35 nations are working together building a huge science complex in the south of France. The international community is spending more than $23 billion on this multinational large-scale scientific experiment to prove the viability of fusion. First plasma is scheduled for 2025 with the start of deuterium-tritium fusion in 2035. It is the largest fusion energy project with commitments from the U.S. of $132 million this year. BNEF anticipates ongoing funding nearing $1 billion through the next decade. The project is not without its critics who contend that commercial fusion will never emerge from the glacial progress of this effort which currently consumes a huge percentage of fusion research dollars.

- The U.S. Department of Energy

The Office of Fusion Energy Sciences (FES) within the DOE Office of Science is providing $50 million for fusion research and plasma science to universities and commercial entities. Ten U.S. multi-institutional research teams will share $30 million for research to sustain high-temperature plasmas for long durations within superconducting tokamak facilities. Recipients include MIT, Princeton Plasma Physics Laboratory, University of Wisconsin-Madison, University of Texas, Austin, Oak Ridge National Laboratory, University of Illinois, General Atomics, and University of California at San Diego, UC Los Angeles, and UC Irvine.

Funding for the Office of FES increased from $380 million in 2017 to $564 million in 2019. Of that latest total, 75% was for basic research with the balance for ITER construction.

The U.S. government is funding the Oak Ridge National Laboratory and Princeton Plasma Physics Laboratory to collaborate with Tokamak Energy in the U.K. demonstrating the global interest in spherical tokamaks and cooperation between private and public organizations.

- DIII-D National Fusion Facility

General Atomics operates this facility for the DOE in San Diego. It is the largest magnetic fusion research effort in the country. General Atomics is also an active participant in ITER for which it is building diagnostic systems as well as the central solenoid which is the world's largest pulsed superconducting electromagnet. The company's Inertial Fusion Technology (IFT) division supplies components, diagnostics and equipment to laboratories in support of DOE's National Nuclear Security Administration's research in inertial confinement fusion and high-energy-density physics.

- ARPA-E

ARPA-E supports potentially disruptive and transformative R&D efforts that are too risky for private development and otherwise not being pursued elsewhere. It is therefore targeting investments in scientific and technological innovations that could accelerate commercially viable fusion. The agency's ALPHA program aims to support lower-cost fusion pathways and to speed its development. Accordingly, its efforts consider additional fusion pathways beyond magnetic and inertial confinement, and focus on intermediate densities between these two approaches. ARPA-E anticipates these new intermediate density options may lead to reduced size, energy, and power-density requirements for economical fusion reactors.

- China's Institute of Plasma Physics

Scientists at China's Institute of Plasma Physics in Hefei are on track to complete construction on a new tokamak reactor HL-2M in 2019 which will bring them closer to delivering nuclear fusion. The institute's Experimental Advanced Superconducting Tokamak (EAST) produced temperatures in 2018 exceeding 100 million degrees Celsius for more than 10 seconds. That temperature represents a seven-fold increase over the sun's core where hydrogen fuses into helium.

- Culham Centre for Fusion Energy (CCFE)

Culham is the site of the Joint European Torus (JET) which is the world's largest magnetic fusion reactor collectively managed by European fusion scientists. JET has been contributing to developments at ITER and is also working to develop fusion power plants. The U.K. government has committed £220 ($283) million for the conceptual design of a Spherical Tokamak for Fusion Energy (STEP) designed to be a commercially-viable fusion plant. The goal is to complete the design by 2024 and construction of the power plant by 2040.

- The Max Planck Institute for Plasma Physics

The Max Planck Institute for Plasma Physics (IPP) in Greifswald, Germany is home to the Wendelstein 7-X stellarator, the largest in the world built at a cost of $407 million. Recent upgrades to the stellarator are aimed at increasing the heating energy to up to 100 million degrees and achieving plasmas that last for 30 minutes. The goal for Wendelstein 7-X is achieving continuous operation which represents the essential advantage of stellarators over tokamaks. IPP collaborates with many research institutions. In October 2019, IPP agreed to work with the University of Wisconsin-Madison to investigate power exhaust from hot stellarator plasmas.

- State of New Jersey

New Jersey is the home to the Princeton Plasma Physics Laboratory and several fusion start-ups. State Senator Joe Pennacchio has introduced local legislation to position the state as a global leader in fusion. Proposals include: defining fusion as a Class 1 renewable energy under the state's renewable portfolio standard; funding scholarships for students in fusion, providing economic incentive programs to fusion technology companies and directing the state's economic development authority to recruit them to New Jersey; and urging Congress to increase funding for fusion energy research.

6. Unresolved challenges

An immediate challenge facing the teams of researchers in the fusion industry is the scientific challenge of devising a scheme for realizing net energy gain. The closest the industry has gotten is 65% return at the JET facility. Once realizing net energy gain, the next challenge is developing an approach that scales to a commercially attractive power plant.

In parallel to technical progress, several fusion companies are developing regulatory and public engagement strategies that will be critical for successful commercialization. Will regulatory agencies and the public lump fusion together with fission, or will there be distinct regulatory approaches that recognize differences between the two technologies? Both British Columbia in Canada and Germany have decarbonization strategies that exclude nuclear fission technologies, yet both have active fusion development activity.

A final, ongoing challenge is finding the resources to support a more aggressive and timely development path to commercialization. Rising concerns over climate change can potentially make this easier – especially if fusion can deliver on its promise of supplying clean, safe and abundant energy as its advocates claim.

Appendices

Appendix A.

7. Fusion company profiles

7.1. Commonwealth Fusion Systems (CFS)

CFS emerged from a student project at MIT's Plasma Science and Fusion Center in 2014. The objective was to reduce the cost of fusion and the founders responded with a new reactor technology that they describe as affordable, robust and compact. The company expects to deliver the first net energy gain fusion SPARC reactor by 2025 that can generate 50MW of heat or electricity using a steam turbine.

MIT research on proprietary magnet technology is integral to CFS. First-of-its-kind, high temperature superconductor magnets will facilitate smaller and lower-cost fusion power plants. In its Series A investment round, CFS raised $115 including $50 million from Italian oil producer Eni, Breakthrough Energy Ventures, and MIT's own investment vehicle for frontier technologies known as The Engine. Other investors in its Series A which closed June 2019 include Future Ventures, Khosla Ventures, Lowercase Capital, Moore Strategic Ventures, Safar Partners, Schooner Capital, and Starlight Ventures. This investment will fund construction of its full scale magnet technology that seeks eventually to deliver a 200MW fusion reactor.

7.2. CTFusion

CTFusion was spun out of DOE-funded research at the University of Washington and is developing sustained spheromaks, compact torus plasma configurations with stabilizing and confining magnetic fields. Spheromaks make the stabilizing toroidal magnetic field with plasma current instead of with superconducting coils. CTFusion says this reduces complexity and size and should translate into more favorable fusion economics.

CTFusion has patented its Imposed-Dynamo Current Drive (IDCD) which enables efficient sustainable stable spheromak configurations. A Phase I, Small Business Innovation Research (SBIR) award from the DOE Office of Science facilitated development of an advanced, graphics processing based feedback control system to optimize the performance of the company's sustained spheromaks. An ongoing ARPA-E project is funding efforts to increase the operating performance of its experimental device. This 24-month, $3 million project started in July 2019, and requires a non-federal cost-share after the first year.

7.3. First Light Fusion

This 2011 spin-off from Oxford University is pursuing a unique approach to fusion that harnesses advanced implosion processes to achieve high temperature and compression. In October, First Light said it expects to demonstrate fusion in 2019, and net energy gain by 2024. The company aims to have its first operating plant supply the grid by the early 2030s. To that end First Light is already working with engineering firm Mott MacDonald on a commercial reactor design. With fusion demonstrated in 2019, the company plans to raise capital to build the gain experiment.

7.4. Fusion Energy Solutions of Hawaii

FESH was founded to provide concentric alternating current particle accelerators for production of fusion reactions. The company's approach abandons the idea of raising temperature and pressure to produce the collision velocities which fusion depends on. Rather, net energy gain depends on a particle accelerator to directly produce collision velocities resulting in fusion. FESH's velocity impact fusion proposes deuterium-deuterium fusion and builds on efforts at Brookhaven National Lab with a linear DC particle accelerator and on a concentric DC particle accelerator at Lawrence Livermore Labs. FESH is funded by its founder and friends and is pursuing Series A funding.

7.5. General Fusion

Founded in 2002 with a goal of commercializing cost-effective fusion power, the company has grown to a team of 70 working in laboratories outside of Vancouver, BC. The company is developing a magnetized target fusion reactor that uses a pressure wave to compress a magnetically-confined plasma fuel to fusion conditions.

General Fusion has received more than $200 million from several venture capital/oil/government investment firms including Chrysalix Venture Capital, Bezos Expeditions, Braemar Energy Ventures, Cenovus Energy, Khazanah Nasional, and from the Canadian government's Sustainable Development Technology Canada fund.

Canada's Strategic Innovation Fund invested $37.5 million in October 2018. Funds will be used to develop a first-of-its-kind, large-scale prototype plant. The company said it intends to raise additional capital to fund the next phase of its technology development, a $350 million fusion demonstration program. The company closed a $65 million Series E equity financing led by Temasek, a Singapore based global investment firm in mid-December 2019.

7.6. Helion

PayPal founder and current venture capital entrepreneur Peter Thiel is one of several investors backing Redmond, Washington-based Helion Energy. The Silicon Valley billionaire together with Y Combinator invested $1.4 million in the company in 2014. The company is developing a magneto-inertial generator that produces power by injecting heated hydrogen and helium at high speed (a million miles an hour) into a "burn chamber." Inside the chamber, a strong magnetic field compresses the plasma to a temperature high enough to initiate fusion. Energy from the reaction is used to generate electricity. It has received nearly $4 million in U.S. DOE grants via ARPA-E and subsequent investment from the Capricorn Investment Group. The company's goal is developing a container sized, 50MW fusion reactor for base load power.

7.7. Hyperjet Fusion

Hyperjet Fusion is developing what was previously known as Plasma-Jet driven Magneto-Inertial Fusion (PJMIF), building on efforts started by the NASA Marshall Space Flight Center, Los Alamos National Laboratory, and HyperV Technologies Corp. With hypersonic jets playing a key role in the fusion approach it now refers to its technology as hyperjet fusion.

NASA, DOE and ARPA-E have funded nearly $28 million of hyperjet fusion research and development. Strong Atomics, a private energy investment fund, has provided $2 million seed funding in 2017 to the Chantilly, Virginia-based company.

7.8. Lawrenceville Plasma Physics

Lawrenceville Plasma Physics (also known as LPP Fusion) is working on a non-tokamak approach called dense plasma focus fusion. The company's goal is a 5MW fusion generator using hydrogen-boron fuel. It's an approach that potentially will produce no neutrons and subsequently eliminate radioactive waste. The design being pursued seeks also to provide direct conversion of electricity absent any turbines and ultimately result in a pathway for cheaper electricity production as the device produces only charged particles. The company's work was initially funded by NASA's jet Propulsion Lab and subsequently funded by the Abell Foundation and through various crowd-sourcing efforts. LPP Fusion has raised $7 million since 2008. It is collaborating with the Center for Energy Research at University of California San Diego, with JET, and the Princeton Plasma Physics Laboratory.

7.9. Lockheed Martin Corp.

Lockheed announced in October 2014 a "compact fusion" project small enough to fit on a truck. At the time, the company suggested its legendary Skunk Works team, which earned the reputation for executing challenging projects quickly and quietly during World War II, could deliver a reactor within 10 years. Lockheed envisions applications for its compact fusion reactor which could produce as much as 100MW of power to include transportation, remote power, desalination and replacement of natural gas turbines.

Lockheed said that its work over the past five years has verified its models and the physics underlying its approach and that its aims to complete a prototype in 2020. The company's 2014 patent describes an open-field magnetic system comprising internal coils to form magnetic fields for confining plasma within a spherical enclosure.

7.10. Proton Scientific

Proton Scientific in Oak Ridge, Tennessee, is developing inertial confinement fusion energy generation which attempts to create economical fusion reactions in a compressed solid fuel pellet. Having raised $4 million in early stage funding in 2019, the company developed an Electron Beam Fusion (EBF) theory and conceptual design of the device applicable to commercial power production. The company's current Thunderbird pulsed-power generator has demonstrated feasibility of the key component of the technology, which is the tightly focused electron beam capable of scaling to fusion ignition energy levels.

In Phase 2 the company expects to complete full assembly and test of the EBF prototype to achieve fusion ignition conditions, the major milestone toward commercial power production, and to begin a design of a full-scale power plant through 2023. The company aims to complete a $20 million Series A funding in 2020 to begin Phase 2 construction of the EBF device with a leading pulsed power provider. The company anticipates the constructed device should demonstrate fusion ignition conditions leading to technology licensing.

The company hopes to raise $1 billion via a Series B offering to fund its 2023-25 Phase III plans. It hopes to implement the power plant core and ready the technology for commercial production of electricity over that time.

7.11. TAE Technologies

Goldman Sachs, Google, and Paul Allen, the now deceased co-founder of Microsoft, are among those that have invested $700 million in TAE Technologies since the company was founded by Noman Rostoker in 1998. The Rockefeller family venture capital farm Venrock and Rusano USA a Russian venture capital firm focusing on nano technologies have also invested in TAE.

The Foothill Ranch, California company's plasma generator has reached temperatures of 35.5 million degrees Fahrenheit and for periods as long 11.5 milliseconds. The company says its approach to fuse hydrogen and boron is the safest and cleanest though it requires higher temperatures than other fusion pathways involving deuterium and tritium. Proton-boron fusion produces positively-charged alpha particles which can induce a current directly in an external conductor.

TAE has partnered with Google to apply the latter's computational prowess and cloud resources to speed the research and development process. Increased processing power has enabled TAE, for example, to process data from images taken by cameras at a rate of 60,000 frames per second. In post-processing, these images are turned into 3D resolved data sets.

7.12. Tokamak Energy

Tokamak is pursuing fusion through the combined development of spherical tokamaks along with high-temperature superconductors. The company, located near Oxford, U.K. aims to deliver a compact tokamak that will generate temperatures in excess of 100 million degrees Celsius fusing deuterium and tritium. The company, which grew out of the Culham Laboratory home of the JET, is currently operating its ST40 tokamak which reached temperatures of 15 million degrees. The company aims to demonstrate net energy gain by 2025 and to deliver a power generation module by 2030. Through the end of 2018 the company had raised GBP 50 million ($65 million). The U.S. DOE is funding Oak Ridge National Laboratory and the Princeton Plasma Physics Laboratory to collaborate with the company.

7.13. Zap Energy

Zap Energy is developing a compact fusion energy solution without using complex and costly magnetic coils. The company is a recipient of a $6.7 million ARPA-E OPEN 2018 award and is in the process of raising an additional $7 million through private investment in 4Q 2019. Under the ARPA-E award, ZAP Energy will seek to reduce the physics risks relating to plasma stability and confinement, and develop electrode technology and plasma-initiation techniques for a functional Z-pinch fusion plant.

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