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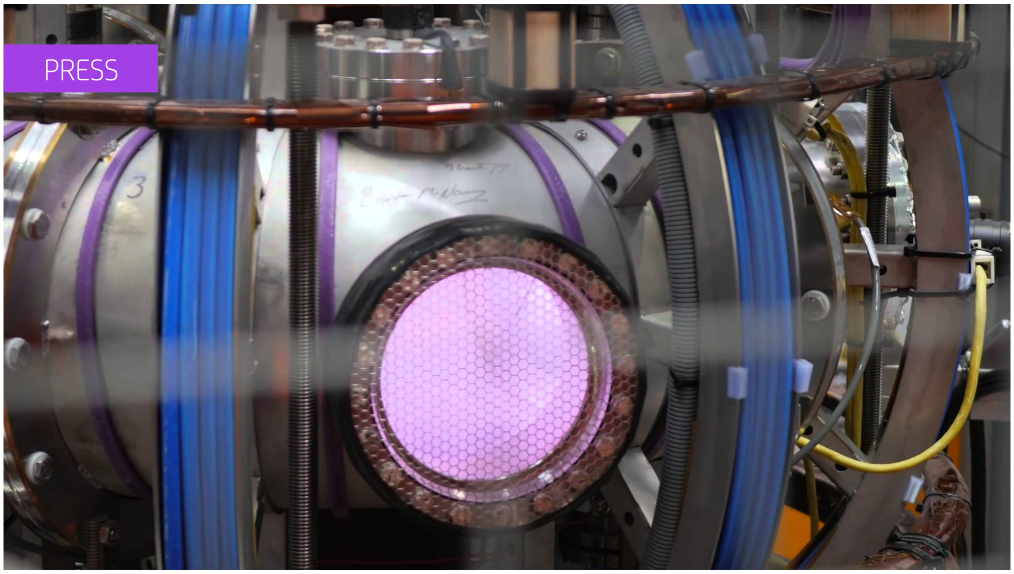


21 September 2015

# Innovation, Collaboration, Funding Needed to Make Fusion a Reality Within a Decade

The quest to produce a carbon-neutral baseload energy source moves higher up the global agenda with every year that goes by. Increasing quantities of renewable energy on the grid; widespread disagreement about the safety of nuclear fission; and growing anxiety about carbon emissions, make the argument for investing in fusion energy a compelling one. If successful, this could be one of the most lucrative opportunities yet.

Fusion reactors would deliver baseload power — ranging from hundreds to thousands of megawatts in capacity, they could be widely distributed to support intermittent renewables and potentially disrupt the energy system at large. Research using more powerful, superconducting magnets to increase plasma pressure inside fusion reactors could mean that fusion power occurs much sooner and at a smaller scale than previously expected. "This puts net energy gain from fusion on a decade timescale," said Professor Dennis Whyte , director of plasma science at the Massachusetts Institute of Technology fusion center. Global collaboration efforts such as ITER have large-scale reach and global recognition, but smaller, privately funded companies may be able to act faster and be more spontaneous. Developments in superconducting magnets could revolutionize the size required for tokamak devices (see panel on right), say scientists at Tokamak Energy Ltd. and MIT, making the systems cheaper and quicker to produce. Meanwhile, companies such as General Fusion Inc. are developing alternative fusion devices.

"Several smaller and more nimble companies are pursuing different varieties of fusion technology in an effort to deliver a power plant that is reliable, practical to build and operate, and competitive in a rather dynamic electricity marketplace," said Chris Gadomski, head of nuclear research at Bloomberg New Energy Finance (BNEF). "They realistically offer a more direct pathway to commercial development than large government-led efforts that are simply focused on proving the science works."

"Tokamaks don't have to be large to be powerful," said Dr David Kingham, chief executive of Tokamak Energy — a company looking to achieve fusion energy in a more compact device than has previously been explored. Kingham agrees with scientists at MIT that increasing the strength of magnetic field and pressure density inside a tokamak through the use of high-temperature superconducting magnets could accelerate the commercialization of fusion power.

"Doubling magnetic field increases fusion power per unit volume by a factor of 16," Whyte said: "Magnetic fields effectively act as an insulator to prevent hydrogen particles from escaping, forcing them to fuse together and form helium."

"Plasma must have a temperature of around 100 million degrees Celsius and the energy has to be confined for approximately 1 second, at a pressure of about 10 atmospheres, in order for fusion to occur," explained Whyte. This can either be done in a very large system — the size of the projected $40 billion ITER project in Southern France — to better maintain heat and maximize the surface area for fusion reactions to occur, or in a system a fraction the size of ITER, using much stronger high temperature semiconductor magnets that remain superconducting at higher magnetic fields. A system about the same size of JET in the U.K. but with nearly triple the magnetic field, could put about 200 megawatts of electric power onto the grid, according to a pilot plant concept developed by the MIT.

Fusion scientists at Tokamak Energy in the U.K., are currently testing a more spherical shaped tokamak of 4 meters in diameter that they say keeps the plasma closest to the area of highest magnetic field surrounding the central column. "At Tokamak Energy we are using smaller, more economical tokamaks that have a higher magnetic field and a smaller surface area of plasma for the magnets to act on," Kingham told Clean Energy and Carbon Brief. "This increases the plasma pressure, thereby increasing the chance for fusion reactions to occur."

Fusion is the process that takes place in the center of stars, whereby hydrogen nuclei subjected to extremely high temperatures and pressure collide and to form fuse heavier helium atoms — destroying a small amount of mass and converting it into huge amounts of energy.

Conditions for fusion on Earth must reach more than 100 million degrees Celsius and gravitational pressure is most often simulated through the use of electromagnets in a tokamak — a donut-shaped metal device.

Deuterium and tritium are two isotopes of hydrogen most commonly used as a fuel, because they are the isotopes that require the lowest temperature to release large amounts of energy. Deuterium is present in water and tritium can be derived from lithium, extractable from the earth's crust.

The heat released when fusion takes place can be harnessed to produce steam to turn turbines — this mechanical energy can then be converted into electrical energy in a generator through a process of induction. Scientists have yet to produce a net energy gain in fusion. The world's current largest tokamak — the Joint European Torus (JET) — located at the Culham Center for fusion energy in the U.K. — produced a record 16 megawatts of energy in 1997 from 24 megawatts of input energy. Fusion Explained Source: Tokamak Energy Ltd. Hydrogen plasma contained in a tokamak using high temperature superconductors. Sept. 21, 2015 Bloomberg Brief Clean Energy & Carbon 11 FOCUS… The Oxford-based company was the first to demonstrate continuous plasma confinement for 29 hours in July 2015. High-temperature superconducting magnets kept the plasma stable.

A key advantage to high temperature superconductors is that they become superconducting around liquid nitrogen temperatures (about 70 degrees above absolute zero) — significantly higher than conventional superconductors that only start to transport current around liquid helium temperatures (around 4 degrees above absolute zero). This significantly reduces the amount of energy required in cooling.

"There is an enthusiasm for fusion energy amongst investors," Kingham said. "They want to get in at an early stage, despite the risks involved." Tokamak Energy has raised over $15 million to date to fund its research, through investment including Oxford Instruments Plc U.K. Institution of , the Mechanical Engineers, and the Rainbow Seed Fund. Each machine operated by the company costs in the region of $2 million, although recent upgrades are expected to increase that figure by 10-15 percent.

Upon proof of feasibility, Tokamak Energy expects manufacturing and material costs to fall significantly. The performance ratio of high-temperature superconductors is expected to improve by a factor of 10 in 5 years, while an installed fusion base could increase dramatically from an initial 100 megawatts to more than 3 gigawatts in 5 years, according to the company website. Patience is of the essence however — Tokamak Energy aims to achieve net energy gain in fusion in 5 years and generation of electricity in ten.

Global aerospace and defence company Lockheed Martin Corp. is also funding research into compact fusion reactors. Its policy is one of small, incremental projects that allow for more rapid and innovative development — the company expects to produce a working fusion prototype in under 5 years. Similar to Tokamak Energy and MIT, higher magnetic fields are being tested in smaller devices to accelerate fusion reactions. This is a "high risk, high pay-off endeavour," said Thomas McGuire, project lead at Skunk Works — the aeronautics unit developing compact fusion prototypes. Nuclear fusion has the potential to keep airplanes aloft for an unlimited time, he says, and could provide an inexhaustible clean energy source.

U.S.-based companies Tri-Alpha Energy Inc. Helion Energy Inc. , and are other companies working to accelerate the progression of fusion energy at a smaller and more economical scale. Helton aims to have a commercial plant operational in six years, according to the company website: At 50 megawatts in scale, Helion's fusion engine will be able to power 40,000 homes for less than $0.04 per kilowatt-hour. The Washington-based company raised $10.6 million in a Series A round in June 2015, over four times the amount expected, according to BNEF data. This followed an angel round of $1.5 million in August 2014, involving investors Mithril Capital Management Y Combinator. and Tri-Alpha raised $40 million in a Series C-2 round in 2007, led by Goldman Sachs Inc. Venrock Vulcan Capital , , , Enel Produzione PIZ Signal NV and , according to BNEF data. The California-based company says its fusion reactor is capable of holding plasma steady at 10 million degrees Celsius for five milliseconds, using a technique whereby two smoke rings of plasma are fired down a 23-meter long tube at nearly a million kilometers an hour, releasing a large amount of energy when they merge in the center.

Magnets at each end of the cigar-shaped tube effectively pen the plasma in. The company uses a fuel mixture of hydrogen and boron — a more naturally abundant element than lithium. Canada-based General Fusion Inc. says its approach could be much lower cost than both magnetic confinement and laser fusion. In May of this year, the company raised $27 million in a Series D funding round, led by Khazanah Nasional Bhd with participation from BDC Venture Capital, Bezos Expeditions, Chrysalix SET, Sustainable Development Technology Canada and Braemar Energy Ventures, according to BNEF data. This round eclipsed previous ones in size – the next largest being a Series B round of $19.5 million in May 2011. A total of $63.9 million has been invested in the company, according to BNEF data. "We create short-lived plasma that has a magnetic field wrapped around, and we compress the plasma, heating it up to fusion conditions," Michael Delage, vice president of technology told Clean Energy and Carbon.

General Fusion's power plant is a large sphere, filled with liquid metal pumped around inside, creating a vortex into which plasma is injected. "All around the sphere is an array of pistons that fire pressure waves through the liquid metal – making the pressure so strong at the center of the sphere that it collapses the vortex, crushing the plasma and heating it up to fusion conditions," he said. The energy released by the plasma is then transferred into the liquid metal, which is pumped into a boiler to create steam — driving both turbines and returning to drive the pistons in a continuous cycle. Commercialization is inherently built into magnetized target fusion, Delage said: The liquid lead tokamak wall is unbreakable and therefore able to withstand long-term exposure to plasma, while "General Fusion can use the steam straight off the boiler to run the pistons, enabling a reasonably high fraction of energy to be recirculated, while still ending up at competitive costs."

Despite the progress made by General Fusion, magnetized target fusion is still a relatively immature technology and far behind development of tokamaks. "We have a lot of progress to do in terms of validating the underlying physics and the developing the subsystems required," Delage said. "Once we group individual pieces together we will move to construct a full-scale demonstration system, but we're not there yet."

ITER is an internationally-unified endeavor to realize net fusion energy gain. At a weight of 23,000 tons, the device will contain a plasma volume of 840 cubic meters, making it the world's largest tokamak fusion device. ITER's goal is to produce 500 megawatts of output power — ten times the amount of energy put in. Located in Cadarache, southern France, the project, which began construction in 2010, is being built collaboratively by the seven ITER members — the U.S., China, European Union, India, Japan, Korea and Russia — each of which provides components.

Total construction costs are estimated at approximately 13 billion euros ($14.6 billion) — Europe will contribute 45.5 percent for construction, while the U.S., China, India, Japan, Korea and Russia will each commit 9.1 percent. For the operation phase (roughly 2019-2037), Europe will assume 34 percent of cost; Japan and the U.S. 13 percent, and the remaining countries 10 percent each. This distributes risk and intellectual property rights, meaning that technology spin-offs in the future could be a possibility.

"The flow of components coming from all over the world will increase over the next 2-3 years, and assembly of the machine will take around 5 years in total," Akko Maas, science engineering officer at the ITER cabinet of director-general, told Clean Energy and Carbon. The project is behind target, due to delays in component arrival, meaning that achieving first plasma by 2020 "is not going to be achievable" he said. However, once deuterium and tritium are introduced "net energy gain will be almost simultaneous," he said.

The ITER machine will be brought online gradually over a period of 7-8 years, with initial plasma tests carried out on pure hydrogen, so that human maintenance and upgrades are possible, before deuterium and tritium fuels are introduced that make the machine radioactive. In contrast to nuclear fission, where atoms are split apart as opposed to fusing together, "a runaway reaction is not possible," Maas said. "If anything goes wrong the reaction stops."

Unlike Tokamak Energy's device, the ITER project will use the more established technology of low-temperature superconducting magnets to generate a magnetic field and confine the plasma.“The bigger the machine the better energy confinement works,” Maas said. This is because the highly energetic helium particles are more likely to remain confined in the plasma with a larger surface area. “It is important that the helium particles that come out of a reaction stay inside the magnetic field and share their gained energy with the rest of the plasma — to maintain the heat and keep the reaction going,” he said. The huge amount of heat contained within the plasma can then be captured and turned into electricity.

However, the aim for ITER is to achieve net fusion energy — “ITER is an experiment, working intermittently, and will therefore not produce baseload power,” Maas said. Usable power production will come at the Demonstration Power Plant stage, currently in conceptual development, in 20-30 years’ time. At this stage, the capacity for DEMO is forecast to be in the region of 2-4 gigawatts. Plans for DEMO depend largely upon the progression of ITER, together with the extent of political will to finance further experiments, said Maas.

Another possibility to be tested at ITER is breeding additional tritium through the fusion reaction itself in a self-sustaining cycle. Excess neutrons that escape from the fusion reactions taking place in plasma will theoretically interact with the lithium in the blanket wall of the tokamak — creating tritium in a nuclear reaction that can then be fed back into the plasma cycle.

Laser fusion, or inertial confinement fusion (ICF), is an alternative to using Laser Fusion magnets to compress fusion fuels to extremely high pressures. This process uses controlled laser beams directed at a target containing fusion fuel that implodes on impact at high velocity, creating sufficient pressure to induce fusion.

The National Ignition Facility in the U.S. contains the largest laser in the world— 60 times larger than any other — which has the ability to fire a laser beam every 4-8 hours. Funded by the U.S. Department of Energy, the purpose of this facility is to maintain the country’s nuclear weapons stockpile safely and securely. “There is 60 times more laser energy going into the reaction than energy released currently,” said Mark Hermann, director of the NIF in an interview with Bloomberg New Energy Finance.“In the distant future, to generate continuous energy, lasers would have to fire pulses to ignite a target ten times per second – much more frequently than the current rate at which we conduct experiments.”

The European high power laser energy research facility (HiPER) will be commissioned next year near Bordeaux, southern France, and is expected to “drive transition from scientific proof of principal [established at NIF] to a demonstration power plant,” according to the HiPER website.

If fusion energy gain proves to be a success, it’s hoped it could, in time, revolutionize the global energy system. The technology is deemed safe and produces no carbon emissions. It’s also said to be incredibly efficient on fuel usage — 1 kilogram of fusion fuel energy is to 10 million kilograms of equivalent fossil fuel. High-temperature superconductors could also have an impact ranging from medical isotope production to magnetized plasma thrusters for space exploration, Whyte said. Speed at which things can be achieved in the fusion industry is dependent on resource access, clarity of communication, and collaboration across private and public funded entities to share ideas. “We should invest in all possibilities — wind, solar, nuclear, fusion,” Maas said. “Because at this moment we do not know what the energy mix will be in 20, 30, 50 years’ time.”

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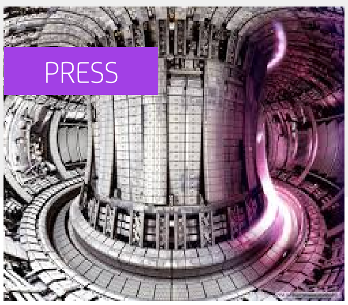

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