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News & Highlights

Start-Ups Seek to Accelerate Path to Nuclear Fusion

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In September 2021, the world's most powerful high-temperature superconducting magnet passed its first test, generating a 20 T magnetic field during a 5 h trial [1]. The 3 m tall, 9000 kg device (Fig. 1) is the centerpiece of an ambitious plan by the start-up Commonwealth Fusion Systems, headquartered in Cambridge, MA, USA, to build a fusion reactor that produces more energy than it requires to stimulate and sustain its nuclear reactions [2,3]. None of the experimental fusion approaches that scientists have tested has come close to that mark. Even the multi-billion USD International Thermonuclear Experimental Reactor (ITER), the massive project sponsored by 35 countries that is under construction in southern France (Fig. 2), is not projected to pass the breakeven point until the mid-2030s at the earliest [2,4]. But Commonwealth Fusion Systems aims to have a pilot plant operating by 2025.

More than 20 other companies and collaborations are also seeking to accelerate the fusion timetable [5], with some claiming they will have commercial reactors in operation within a decade or so [6,7]. Skeptics say they have heard big promises before—the old joke is that a working fusion reactor is always just 30 years away [8]. However, researchers and engineers have made key advances in fields such as materials and computer modeling and control systems, and they have gained a much better understanding of high-temperature plasma (Fig. 3), the gas-like state of matter that all fusion designs depend on. As a result, "there are multiple clear paths to a working reactor that could happen sooner rather than later," said Christopher Holland, a research scientist at the Center for Energy Research at the University of California, San Diego. And investors have bought into the idea that fusion will soon be feasible—to the tune of more than 2 billion USD [9].

Still, Holland and other experts caution, formidable engineering hurdles stand in the way of a practical fusion reactor, including how best to shield the device from its own byproducts and how to provide tritium, one component of the nuclear fuel in most designs [10]. Engineers will eventually find solutions to these challenges, said Stephen Dean, a physicist and president of Fusion Power Associates, a Maryland-based foundation that promotes fusion research and development. "But it is going to take longer than ten years."

Nuclear fusion offers several advantages over the fission reactions that power all the world's commercial nuclear plants. Fission reactors capture the energy unleashed when bulky atoms—typically U^{235}—break apart, whereas fusion reactors produce power from the energy liberated when small atoms—usually tritium and a second hydrogen isotope, deuterium—combine [11]. A fusion reactor can generate four times as much energy per gram of fuel as a fission reactor, will not melt down, and does not yield high-level nuclear waste [12]. In principle, fusion power plants could supply vast amounts of low-carbon electricity and thus help combat climate change [10].

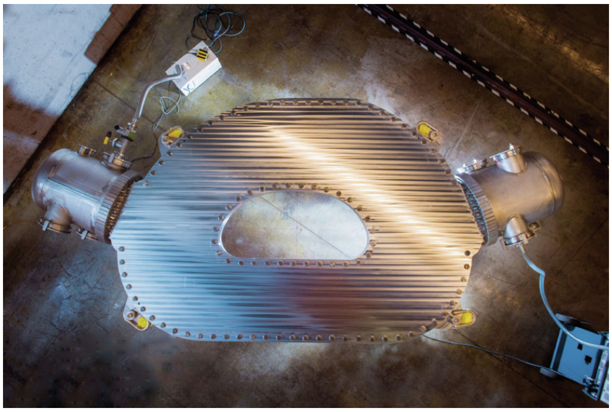

Fig. 1. Viewed from above, this superconducting magnet from Commonwealth Fusion Systems can generate a 20 T magnetic field at a temperature of −263 °C. The company plans to build a pilot plant that will use multiple such magnets to control a plasma by 2025, in what could become the first reactor to generate more energy than its fusion reactions require. Credit: Gretchen Ertl, CFS/MIT-PSFC, 2021 (public domain).

But as one commentator put it, developing a working, practical reactor is "arguably the most difficult engineering challenge humans have ever attempted" [13]. The device must squeeze together positively charged nuclei that strongly repel each other. The extreme heat of plasmas—the one swirling around within ITER will reach 1.5×10^8 °C, ten times hotter than the Sun's interior [14]—may force standoffish nuclei to combine. The challenges that engineers must solve to make fusion reactors feasible include generating the plasma and maintaining it long enough to incite fusion; protecting the reactor from high temperatures and neutrons; and transforming the resulting energy into electrical power.

The best-studied technology for harnessing plasmas is the tokamak, a reaction chamber shaped like a donut or cored apple that was invented in the 1950s [13]. Powerful magnets surrounding the device create a magnetic field that bottles up the plasma,

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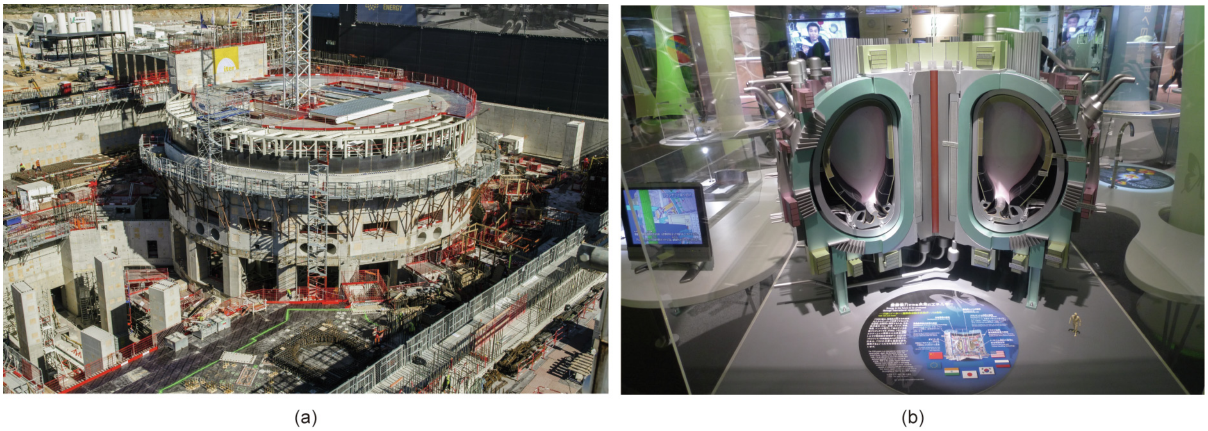
(a)
(b)

Fig. 2. (a) ITER, shown here under construction in 2018, will contain a total of 10 000 t of superconducting magnets cooled to −269 °C that will trap and control its plasma. Credit: Oak Ridge National Laboratory (CC BY 2.0). (b) With an interior volume of 830 m^3, the ITER tokamak, a model of which is shown here, will be the largest in the world. Credit: Motokoka (CC BY 2.0).

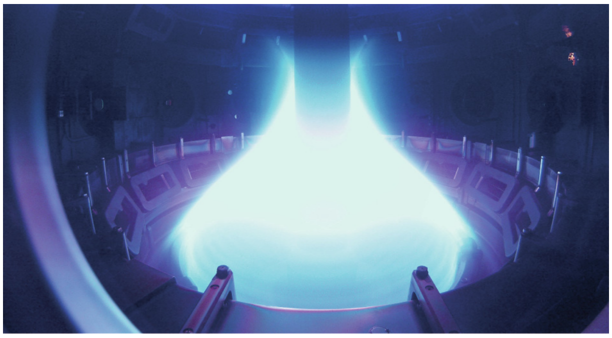

Fig. 3. A searing plasma glows in the Mega Ampere Spherical Tokamak in Culham, Oxfordshire, UK, which generated more than 30 000 plasmas between 1999 and 2013. Credit: Eye Steel Film (CC BY 2.0).

keeping it hot and preventing it from damaging the walls of the chamber. More than 100 of these machines have been built around the world since the 1950s, and they remain popular—ITER is a tokamak. Scientists are exploring a variety of other approaches as well. One example is the National Ignition Facility at the Lawrence Livermore National Laboratory in California, USA, an array of 192 lasers that heats fuel capsules to more than 3×10^6 °C, triggering deuterium and tritium in the capsules to fuse [15].

Using electricity, particle beams, and other energy sources, researchers have jumpstarted short-lived plasmas. In 2021, for instance, China's Experimental Advanced Superconducting Tokamak (EAST) maintained a plasma at an average temperature of 1.2×10^8 °C for 101 s [16]. So far, no reactor has produced a burning plasma, in which fusion reactions furnish most of the energy to keep the plasma at extreme temperatures [17]. "We think we can do that now. It is a vital first step," said Holland. A burning plasma is a prerequisite for achieving net energy gain, the ultimate goal for fusion devices in which the reactions produce more energy than is necessary to incite and maintain them [18].

The record performance for a tokamak is an output-to-input ratio of just under 0.7. In a fusion power plant, however, the reactions would need to give off more than 15 times more energy than they consume [19]. That is partly because only a fraction of the energy released by combining atoms can be captured for power generation. Fusion reactors will also need large amounts of electricity to operate. An example of power-hungry fusion technology, said Saskia Mordijck, an assistant professor of physics at William and Mary College in Williamsburg, VA, USA, is the superconducting magnets that confine the plasma. ITER's magnets must remain at −269 °C and chilling them to that temperature requires the world's largest helium cooling system [14].

ITER, which is scheduled to reach "first plasma" in 2026, will not generate electricity. But assuming the project produces a burning plasma and achieves net energy gain as planned, experts say it will provide important data and experience that will help them improve the design of commercial reactors. Still, ITER will not resolve several key engineering issues. One uncertainty is the best material for lining the reaction chamber [20]. Not only does this material have to withstand the plasma's heat, but it also will be pelted by neutrons generated in fusion reactions, which can cause damage. Another unresolved issue is how to produce the tritium the reactors need [20]. Scientists envision coating tokamaks with a blanket of lithium, which yields tritium when bombarded by neutrons. Whether the blanket can supply enough tritium remains unclear, however. "I do not see commercial fusion reactors until those two engineering challenges are solved," said Mordijck.

More and more countries have decided that the best way to learn how to overcome these and other engineering obstacles is by doing. The United Kingdom is looking to have a prototype government-funded reactor running by 2040, and China could have one even sooner [21,22]. And if the United States follows the latest advice from two groups of experts, it will harness public–private partnerships to open a pilot facility no later than the 2040s [23,24].

The more than a dozen private companies pursuing fusion say they can beat those deadlines—and at a lower price. New technology may give them a boost. For example, ITER's magnets need to remain so cold because they use older superconducting materials—niobium-containing wires [25]. Commonwealth Fusion Systems' magnets contain a tape coated with rare earth barium copper oxide that works best at −263 °C instead of −269 °C [26]. The magnets will be smaller but more powerful than ITER's—and potentially cheaper to build and operate [26]. The company says its reactor should cost much less than ITER.

Commonwealth Fusion Systems is one of several companies sticking with tokamaks—either the donut or the cored apple varieties. But other competitors are evaluating an assortment of novel reactor configurations. The latest machine from Foothill Ranch, CA, USA-based TAE Technologies, for instance, is a 24 m long tube that generates ring-shaped plasmas at each end and then propels them together at high speeds to create fusion conditions [27]. General Fusion, based in Vancouver, BC, Canada, plans to complete a 400 million USD demonstration plant in the United Kingdom by 2025. This device will inject plasma into a chamber containing molten lead and lithium. Pistons will compact the molten metal, which in turn will squeeze the plasma until fusion occurs [28].

If any of the current efforts results in a fusion power plant that generates electricity, that would be a huge accomplishment, said Dean. But it would only be one step toward commercialization of fusion, he added. Companies would then need to show that they can build plants that will compete with other sources of power in energy markets. “It is entirely going to be a matter of cost,” he said.

References

[1] Cho A. This powerful electromagnet could help make fusion energy a reality [Internet]. Washington, DC: Science; 2021 Sep 8 [cited 2021 Oct 18]. Available from: https://www.science.org/content/article/powerful-electromagnet-could-help-make-fusion-energy-reality.

[2] Jordans F, Borenstein S, Cole D. Magnet milestones move distant fusion dream closer [Internet]. New York City: AP News; 2021 Sep 9 [cited 2021 Oct 18]. Available from: https://apnews.com/article/technology-sports-france-climate-environment-and-nature-029d14f22aaabe1a33030f612d8fc52a.

[3] Proctor D. The POWER interview: designing a net energy fusion system [Internet]. Houston: Power; 2020 Oct 26 [cited 2021 Oct 18]. Available from: https://www.powermag.com/the-power-interview-designing-a-net-energy-fusion-system/.

[4] Tirone J. Fusion reactor waylaid by latest waves of COVID pandemic [Internet]. New York City: Bloomberg Green; 2021 May 10 [cited 2021 Oct 18]. Available from: https://www.bloomberg.com/news/articles/2021-05-10/fusion-reactor-waylaid-by-latest-waves-of-covid-pandemic.

[5] Markoff J. Massachusetts start-up hopes to move a step closer to commercial fusion [Internet]. New York City: New York Times; 2021 Aug 10 [cited 2021 Oct 18]. Available from: https://www.nytimes.com/2021/08/10/technology/commonwealth-fusion-mit-reactor.html.

[6] Kramer D. Investments in privately funded fusion ventures grow [Internet]. Melville: Physics Today; 2020 Oct 13 [cited 2021 Oct 18]. Available from: https://physicstoday.scitation.org/do/10.1063/PT.6.2.20201013a/full/.

[7] Patel P. General fusion takes aim at practical fusion power [Internet]. New York City: IEEE Spectrum; 2021 Aug 13 [cited 2021 Oct 21]. Available from: https://spectrum.ieee.org/general-fusion-takes-aim-at-practical-fusion-power.

[8] Garisto D. Has fusion really had its “wright brothers” moment? [Internet]. New York City: IEEE Spectrum; 2021 Aug 27 [cited 2021 Oct 18]. Available from: https://spectrum.ieee.org/has-fusion-really-had-its-wright-brothers-moment.

[9] Turrell A. The race to give nuclear fusion a role in the climate emergency [Internet]. London: The Guardian; 2021 Aug 28 [cited 2021 Oct 18]. Available from: https://www.theguardian.com/environment/2021/aug/28/the-race-to-give-nuclear-fusion-a-role-in-the-climate-emergency.

[10] National Academies of Science, Engineering, and Medicine. Bringing fusion to the US grid. Washington, DC: The National Academies Press; 2021.

[11] Fission and fusion: what is the difference? [Internet]. Washington, DC: United States Department of Energy; 2021 Apr 1 [cited 2021 Oct 18]. Available from: https://www.energy.gov/ne/articles/fission-and-fusion-what-difference.

[12] Advantages of fusion [Internet]. St. Paul-lez-Durance: International Thermonuclear Experimental Reactor; c2021 [cited 2021 Oct 18]. Available from: https://www.iter.org/sci/Fusion.

[13] Clynes T. 5 big ideas for making fusion power a reality [Internet]. New York: IEEE Spectrum; 2020 Jan 28 [cited 2021 Oct 18]. Available from: https://spectrum.ieee.org/5-big-ideas-for-making-fusion-power-a-reality.

[14] Moskowitz C. World’s largest fusion reactor begins assembly [Internet]. New York City: Scientific American; 2020 Dec 1 [cited 2021 Oct 18]. Available from: https://www.scientificamerican.com/article/worlds-largest-fusion-reactor-begins-assembly/.

[15] How ICF works [Internet]. Livermore: Lawrence Livermore National Laboratory; [cited 2021 Oct 18]. Available from: https://lasers.llnl.gov/science/icf/how-icf-works.

[16] Delbert C. China’s Artificial Sun just smashed a fusion world record [Internet]. New York City: Popular Mechanics; 2021 Jun 7 [cited 2021 Oct 18]. Available from: https://www.popularmechanics.com/science/energy/a36630528/china-artificial-sun-breaks-fusion-world-record/.

[17] DOE explains…burning plasma [Internet]. Washington, DC: United States Department of Energy; [cited 2021 Oct 18]. Available from: https://www.energy.gov/science/doe-explainsburning-plasma.

[18] Overton T. Fusion energy is coming, and maybe sooner than you think [Internet]. Houston: Power; 2020 Jun 1 [cited 2021 Oct 18]. Available from: https://www.powermag.com/fusion-energy-is-coming-and-maybe-sooner-than-you-think/.

[19] Barbarino M. On the way to fusion power: burning plasmas, mastering energetic particles and taming instabilities [Internet]. Vienna: International Atomic Energy Agency; 2019 Sep 10 [cited 2021 Oct 18]. Available from: https://www.iaea.org/newscenter/news/on-the-way-to-fusion-power-burning-plasmas-mastering-energetic-particles-and-taming-instabilities.

[20] Powering the future: fusion and plasmas [Internet]. Washington, DC: United States Department of Energy; c2020 [cited 2021 Oct 18]. Available from: https://usfusionandplasmas.org/.

[21] Gibney E. UK hatches plan to build world’s first fusion power plant [Internet]. London: Nature; 2019 Oct 11 [cited 2021 Oct 18]. Available from: https://www.nature.com/articles/d41586-019-03039-9.

[22] Chen S. China’s “Artificial Sun” tipped to provide electricity in 10 years if Beijing backs it [Internet]. Hong Kong: South China Morning Post; 2021 Sep 29 [cited 2021 Oct 25]. Available from: https://www.scmp.com/news/china/science/article/3150464/chinas-artificial-sun-tipped-provide-electricity-10-years-if.

[23] Cho A. Road map to US fusion power plant comes into clearer view—sort of [Internet]. Washington, DC: Science; 2021 Feb 19 [cited 2021 Oct 18]. Available from: https://www.science.org/news/2021/02/road-map-us-fusion-power-plant-comes-clearer-focus-sort.

[24] Cho A. US physicists rally around ambitious plan to build fusion power plant [Internet]. Washington, DC: Science; 2020 Dec 8 [cited 2021 Oct 18]. Available from: https://www.science.org/news/2020/12/us-physicists-rally-around-ambitious-plan-build-fusion-power-plant.

[25] Clery D. Magnet challenges for ITER [Internet]. Bristol: Physics World; 2011 Sep 29 [cited 2021 Oct 18]. Available from: https://physicsworld.com/a/magnet-challenges-for-iter/.

[26] Clery D. Fusion startup plans reactor with small but powerful superconducting magnets [Internet]. Washington, DC: Science; 2021 Mar 3 [cited 2021 Oct 18]. Available from: https://www.science.org/content/article/fusion-startup-plans-reactor-small-powerful-superconducting-magnets.

[27] Clifford C. Look inside this lab where scientists are recreating the energy of the sun to produce nearly unlimited clean energy [Internet]. New York City: CNBC; 2021 Apr 30 [cited 2021 Oct 18]. Available from: https://www.cnbc.com/2021/04/30/photos-inside-tae-technologies-lab-and-nuclear-fusion-machine.html.

[28] The race to build a commercial fusion reactor hots up [Internet]. London: The Economist; 2021 Jun 26 [cited 2021 Oct 18]. Available from: https://www.economist.com/science-and-technology/2021/06/24/the-race-to-build-a-commercial-fusion-reactor-hots-up.