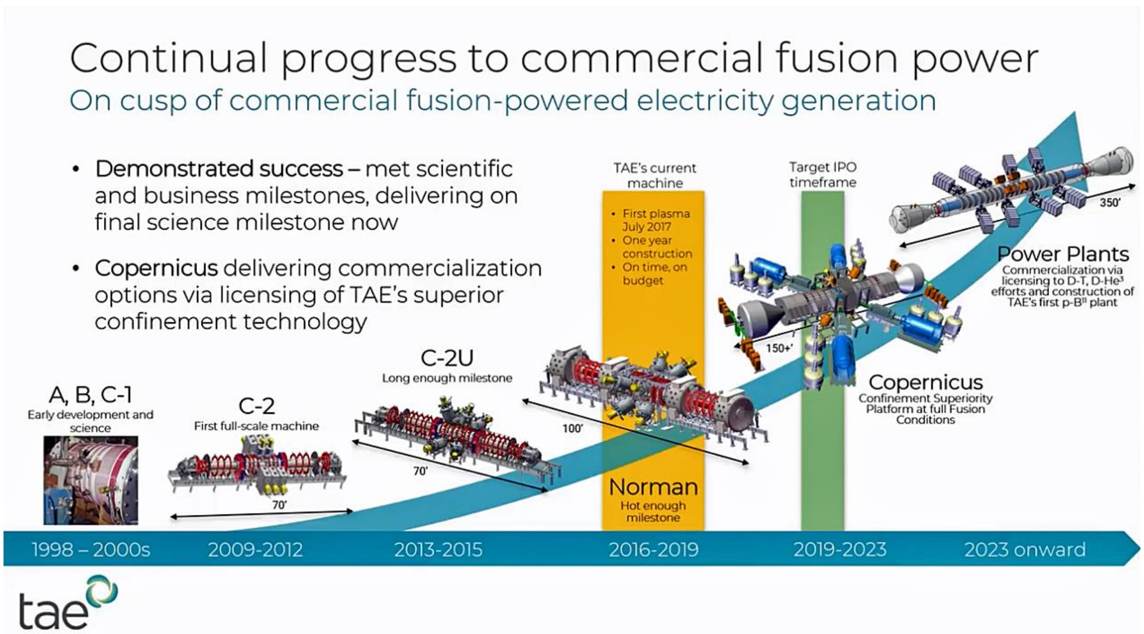
The Fork in the Road to Electric Power From Fusion

TAE Technologies (formerly Tri Alpha Energy)

Peter Lobner, 1 February 2021

TAE Technologies was founded by George Sealy, Harry Hamlin, and Andrew Conrad in 1998 in Foothill Ranch in Orange County, CA. Their goal is to pursue the development of a pulsed, accelerator-driven, colliding beam fusion reactor. Norman Rostoker was the original CEO with Michl Binderbauer as Chief Technical Officer, and now CEO.

In more than two decades, TAE Technologies has developed a series of experimental machines and compiled an extensive portfolio of patents related to their accelerator technologies. The following timeline highlights TAE's past and planned future developments. The TAE website is here: https://tae.com



TAE fusion reactor development timeline. Source: TAE Technologies

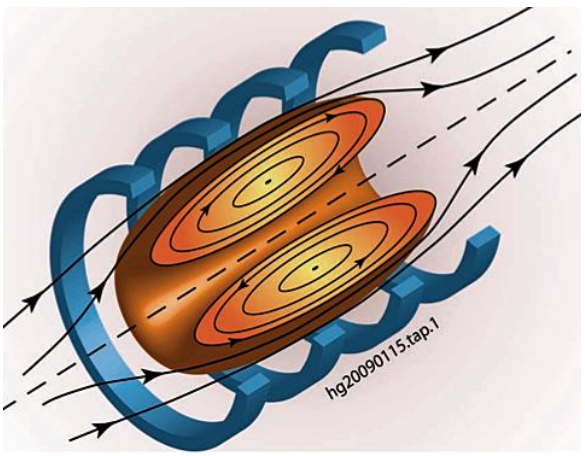
The TAE concept for a commercial fusion power plant is based on aneutronic hydrogen (proton) / boron-11 (p-B11) fusion, which can be triggered at an extremely high temperature of about 3 billion °C by the following reaction:

$$^{1}p + ^{11}B \rightarrow 3\ ^{4}He + 8.7\ MeV$$

The Fork in the Road to Electric Power From Fusion

This fusion reaction does not generate neutrons. Energy generated by fusion is carried off by three positively charged alpha particles, which creates an opportunity for direct conversion into electricity, without the need for a thermal cycle power conversion system. The TAE fusion machine also can be used for D-T and D-Helium-3 fusion, which occur at much lower temperatures than p-B11 fusion, at about 100 million °C and 800 million °C, respectively.

The pulsed, colliding beam linear accelerator at the heart of TAE's fusion machine starts each pulse cycle by creating "field reversed configuration" (FRC) plasma targets in plasma guns at opposite ends of the accelerator. An FRC plasma target (plasmoid) is in the form of a self-stable plasma torus, similar to a smoke ring.



Source: TAE Technologies

The FRC plasma targets are "fired" simultaneously, accelerated toward each other and then collide in a central confinement chamber where the merged FRC target plasma is heated further by neutral beam injectors to produce a fusion reaction.

TAE's first full-scale machine was the C-2, which entered operation in about 2000. The C-2 design was the basis for the machine described in several TAE patents, patents, including US10049774, which was granted in 2018. The C-2 machine included "systems and methods that facilitated forming and maintaining High Performance Field Reversed Configurations (FRCs) with superior stability as well as superior particle, energy and flux confinement over conventional FRCs." The degree of improvement is shown in patent Figure 1.

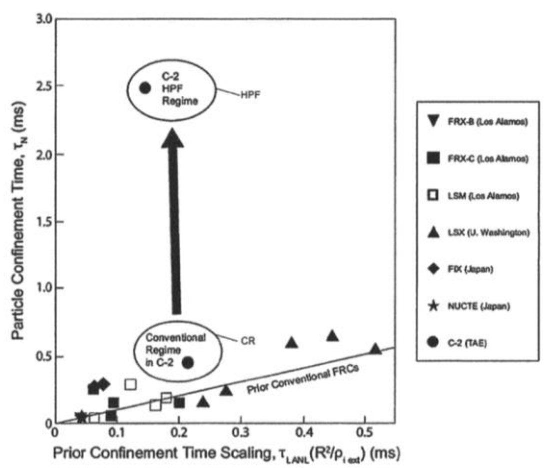


FIGURE 1

The general arrangement of the C-2 machine, as viewed from the top, is shown in patent Figure 3A. The plasma guns (350) are at the left and right ends of the machine. The several neutral beam injectors (610, 640) fire beams of fast neutral atoms into the central confinement chamber, tangentially to the FRC plasma. This heats the FRC, supplies it with fresh fuel, and stabilizes it by keeping the spin rate up.

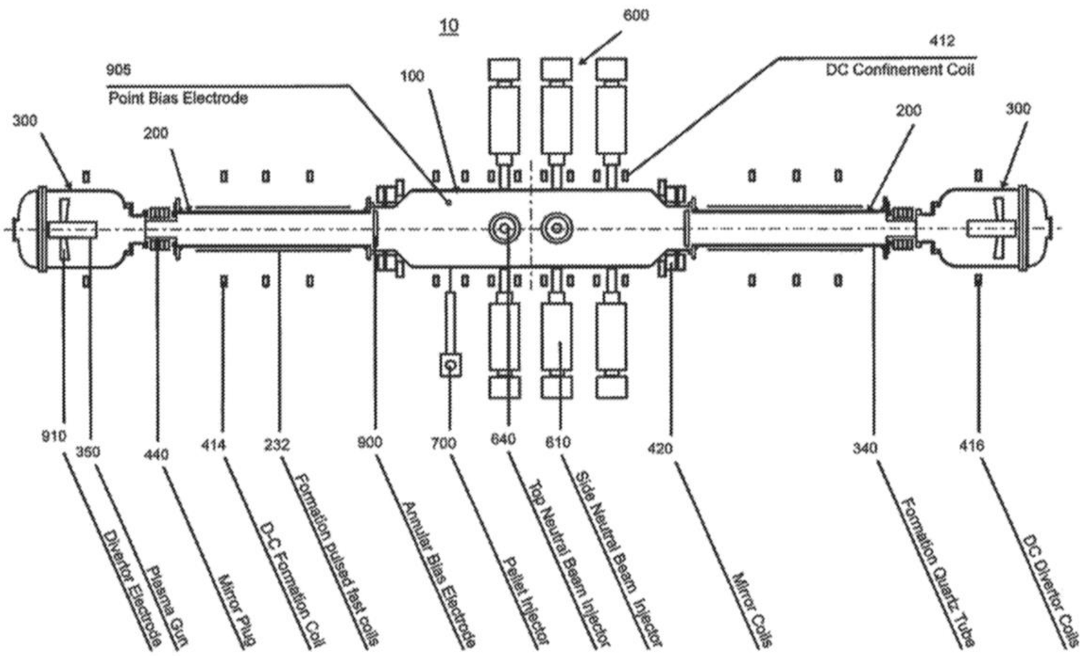


FIGURE 3A

Patent figure 2 illustrates the magnetic topology inside the C-2 machine during a shot, with the merged FRC plasma in the central confinement chamber.

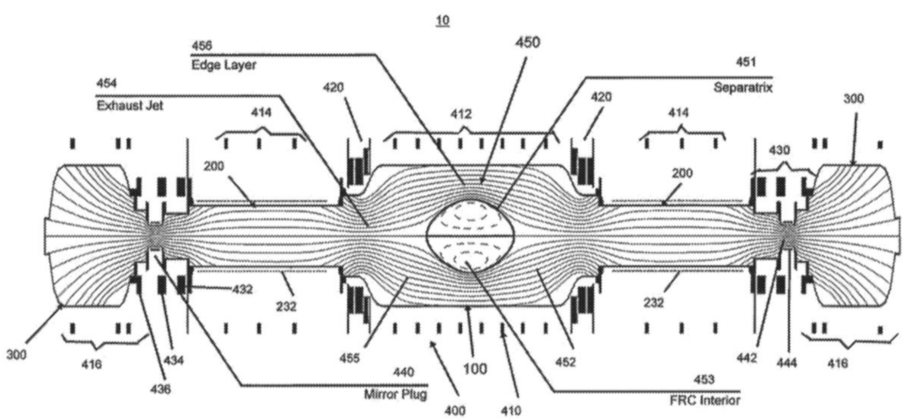
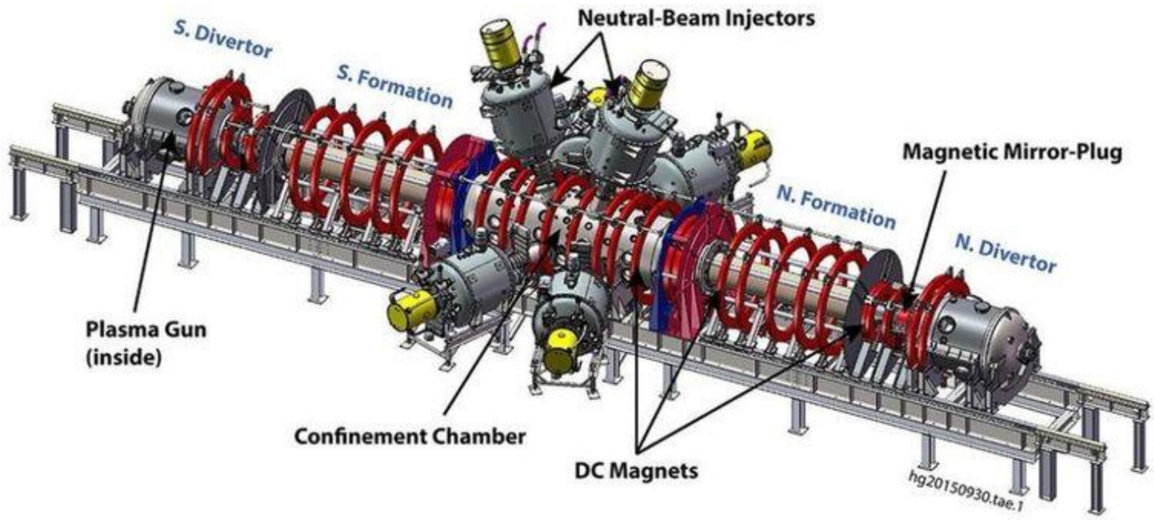


FIGURE 2

The next design iteration was the C-2U, which achieved a hydrogen plasma temperature of >10 million °C, about the temperature of the sun's core, for 10 milliseconds.



General arrangement of the 70 ft (21.3 m) long fourth-generation C-2U fusion machine. The FRC targets are generated by plasma guns at each end and accelerated to merge at the central confinement chamber. Source: TAE Technologies

TAE's fusion machines have thousands of configurable parameters that can affect the outcome of a "shot." Through their collaboration with Google, which started in 2014, TAE and Google researchers were able to optimize the C-2U fusion machine in 2017 using a process called the "Optometrist Algorithm,"

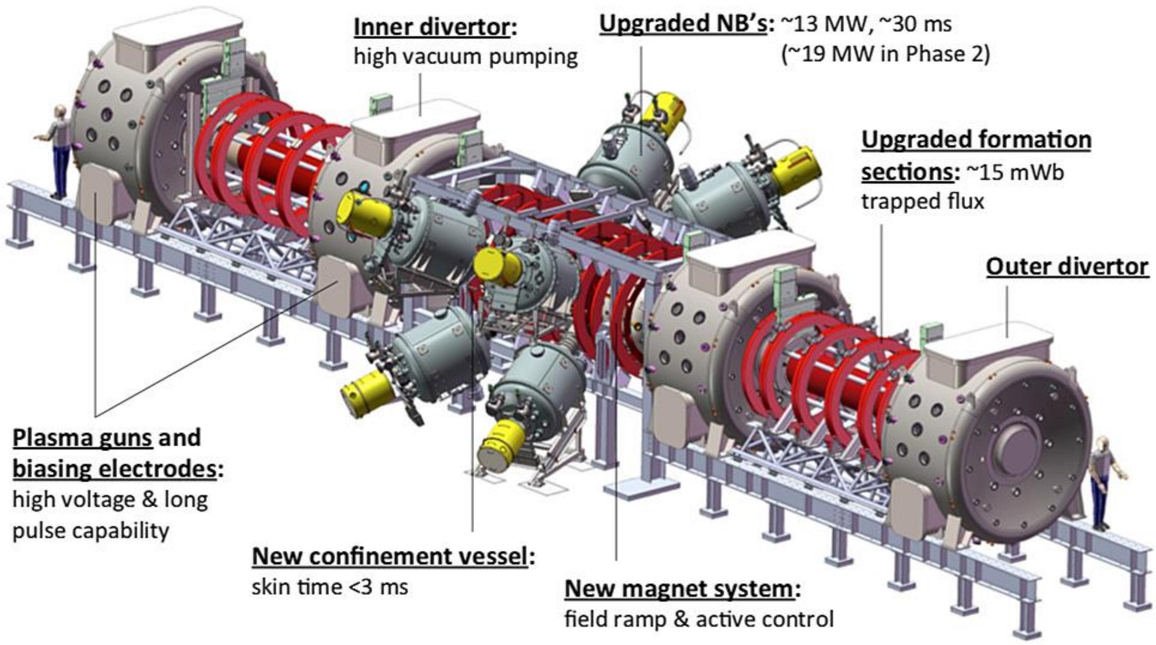
> "To efficiently optimize the system, we develop the Optometrist Algorithm, a stochastic perturbation method combined with human choice. Analogous to getting an eyeglass prescription, the Optometrist Algorithm confronts a human operator with two alternative experimental settings and associated outcomes. A human operator then chooses which experiment produces subjectively better results. This innovative technique led to the discovery of an unexpected record confinement regime with positive net heating power in a field-reversed configuration plasma, characterized by a >50% reduction in the energy loss rate and concomitant increase in ion temperature and total plasma energy."

You'll find a paper on their use of the Optometrist Algorithm at the following link: https://www.nature.com/articles/s41598-017-06645-7#citeas

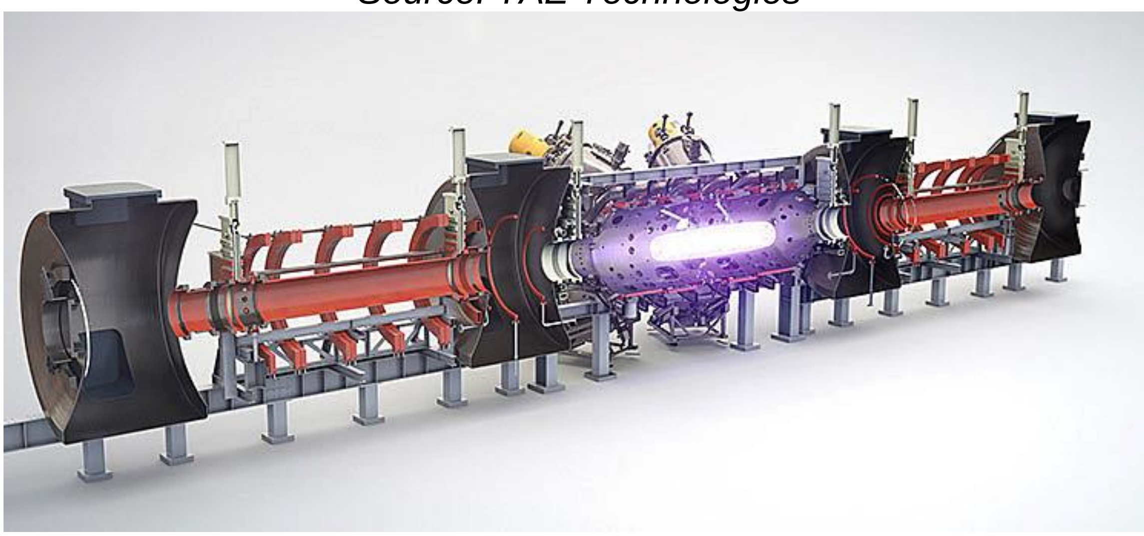
In July 2017, TAE announced that its $100 million fifth-generation C-2W machine, nicknamed "Norman" (after the company's late co-founder, Norman Rostoker), achieved first plasma. By early 2018, it had exceeded the plasma stability and temperature performance of the C-2U. Norman is not designed to reach breakeven.

In 2019, TAE reported they were performing 60 shots per day and getting 10 gigabytes of data per shot. Google has supported TAE in implementing artificial intelligence and machine learning for data processing, which enables them to process shot data in 3-4 seconds.

End-on view of Norman and the TAE team.
Source: TAE Technologies.

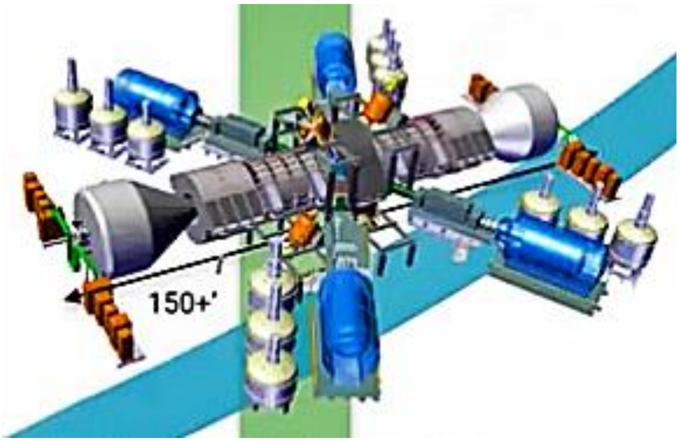


General arrangement of the 100 ft (30.5 m) long fifth-generation C-2W Norman fusion machine, highlighting upgrades. Source: TAE Technologies



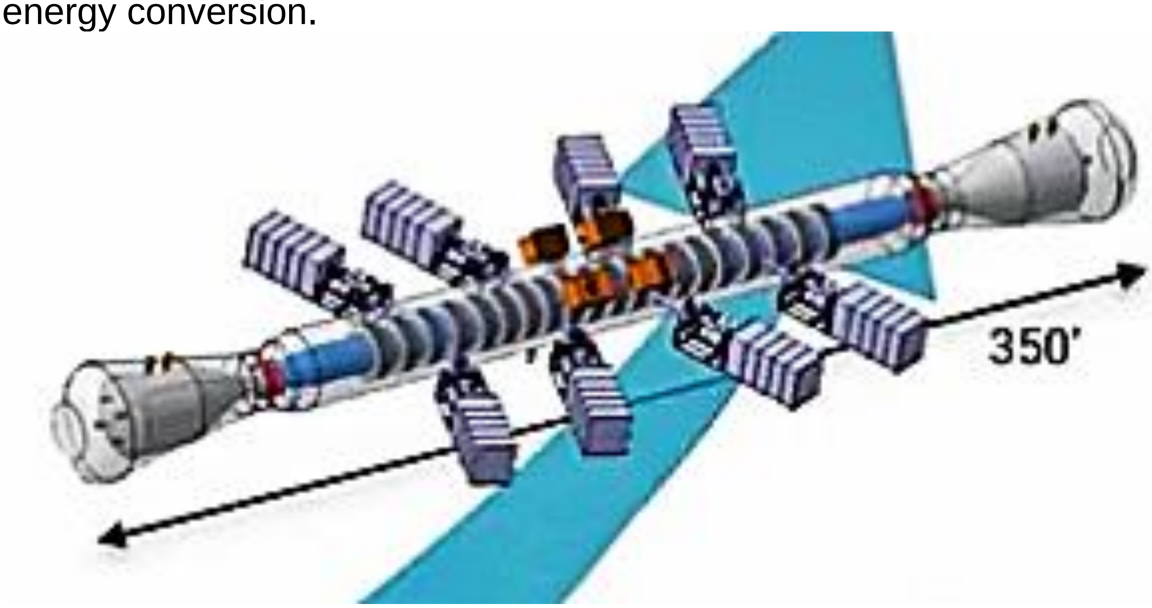
Cross-section rendering of the fifth-generation C-2W Norman fusion machine. The plasma region in the central confinement vessel is about eight feet (2.4 m) long and is sustained by tangential beams from the neutral beam injectors. Source: TAE Technologies

The next larger machine, Copernicus, is planned for the early 2020s, as shown in the TAE timeline. Copernicus will be a 150+ ft (45.7+ m) long, reactor-scale device designed to achieve >100 million °C plasma temperatures and demonstrate a net energy gain (Q > 1.0) with deuterium – tritium (D-T) fusion. Copernicus will be an intermediate step on the way to building a commercial fusion reactor that is capable of operating at the much higher plasma temperatures needed for p-B11 fusion.



Concept drawing for the D-T fusion Copernicus.
Source: TAE Technologies

Beyond Copernicus, TAE is planning to build a larger device named Da Vinci that would be their prototype for a commercial fusion power reactor. This prototype may be built as soon as the late 2020s. It is planned to be an aneutronic p-B11 fusion machine with a net electrical power output of 350 – 400 MWe, presumably by direct energy conversion.



Concept drawing for a p-B11 fusion commercial power plant.
Source: TAE Technologies

TAE claims that direct energy conversion can be achieved with an inverse cyclotron converter (ICC) that can handle the high-energy alpha particles produced by p-B11 fusion. The linear motion of charged alpha particles produced from fusion is converted to circular motion by a magnetic cusp. Energy is collected from the charged particles as they spiral past quadrupole electrodes.

TAE estimated that the plant overnight capital cost will be about $4,300/kW ($4.3/W) and $1.5 - $1.7 billion total. These values are within the $5/W and $2 billion total overnight capital cost targets recommended by the Department of Energy’s (DOE) Advanced Research Project Agency – Energy (ARPA-E). The levelized cost of electricity is estimated to be about 8¢ / kWh.

TAE reported that they do not plan to be a commercial fusion equipment or power plant supplier, which they regard as low margin businesses. Instead, they plan to license the technologies for their fusion reactors.

Funding

TAE is backed almost entirely by investments from venture capital firms, large corporations and private investors. In October 2020, *Physics Today* reported that TAE had raised about $750 million in funding for their fusion program and has a valuation of about $3 billion.

After an initial round that raised $1.7 million unknown investors in January 2000, TAE Technologies has had six investment rounds:

- Series A (2001) & A-2 (2002): $4.93 million from Paul Allen and an unknown investor
- Series B (2003): $6.67 million from Vulcan Ventures (Paul Allen)
- Series C (2005) & C-2 (2007): $79.41 million from Vulcan Ventures, Venrock, Goldman Sachs, New Enterprise Associates and others

- Series D (2010) & D-2 (2013): $177 million from New Enterprise Associates, Big Sky Partners and Rusnano (a Russian state owned firm)
- Series E (2015): $127.5 million from an unknown investor
- Series F (2016): $375 million from Alphabet, For Good Ventures and Wellcome Trust

In addition, DOE has provided the following funding:

- In November 2017, TAE was awarded a DOE INCITE grant (Innovative and Novel Computational Impact on Theory and Experiment) that gave the firm access to a DOE Cray XC40 supercomputer to support their modeling and simulation work.
- In 2019 and 2020, TAE received a total of six awards in three rounds of funding under the DOE FES INFUSE program (Innovation Network for Fusion Energy).

For more information

- S. Putvinski, "pB11-reactor: Trends and physics issues," Tri-Alpha Energy, 18 August 2015: https://www.physics.uci.edu/sites/physics.uci.edu/files/P20-FRC-reactor-Rostoker-08-18-2015-final.pdf
- Jay Bennett, "Google's Nuclear Fusion Project Is Paying Off," Popular Mechanics, 24 July 2017: https://www.popularmechanics.com/science/green-tech/news/a27484/google-fusion-energy-company-improve-plasma-reactor-ai/
- E.A. Blatz, et al., "Achievement of Sustained Net Plasma Heating in a Fusion Experiment with the Optometrist Algorithm," Scientific Reports, 7, 6425, 2017: https://doi.org/10.1038/s41598-017-06645-7
- G. Gota & M. Binderbauer, "Status Update on Tri Alpha Energy's Fusion Program," ARPA-E ALPHA Annual Review Meeting, 30 August 2017: https://arpa-e.energy.gov/sites/default/files/9_GOTA.pdf
- Alan Boyle, "TAE fusion venture wins supercomputer time — and reports progress on test device," GeekWire, 30 November

2017: https://www.geekwire.com/2017/tae-fusion-supercomputer/

- "TAE Technologies' Fusion Machine Exceeds Prior Operations and Performance Levels in Record Time," CISION PR Newswire, 6 February 2018: https://www.prnewswire.com/news-releases/tae-technologies-fusion-machine-exceeds-prior-operations-and-performance-levels-in-record-time-300593002.html
- Brian Wang, "CEO of TAE Technologies Says They Will Begin Commercialization of Fusion by 2023," NextBigFuture, 16 January 2019: https://www.nextbigfuture.com/2019/01/ceo-of-tae-technologies-says-they-will-reach-commercial-fusion-by-2024.html
- Jack Hare, "New calculations show proton-boron fusion is still difficult," Fusion and Things, 5 June 2019: http://fusionandthings.eu/2019/06/05/new-calculations-show-proton-boron-fusion-is-still-difficult/ "Fusions Path to Practicality," DOE Office of Science, 8 July 2019: https://www.energy.gov/science/articles/fusions-path-practicality
- "TAE Technologies Wins Three INFUSE Awards to Further Fusion Energy Research," CISION PR Newswire, 4 December 2019: https://www.prnewswire.com/news-releases/tae-technologies-wins-three-infuse-awards-to-further-fusion-energy-research-300968932.html
- "TAE Technologies Furthers Fusion Research With National Labs," CISION PR Newswire, 8 October 2020: https://www.prnewswire.com/news-releases/tae-technologies-furthers-fusion-research-with-national-labs-301148795.html

Video

- The 2019 video, "ACA Fireside Chat with Harry Hamlin and Michl Binderbauer" (44:16 minutes) provides interesting insights to TAE's history and its plans for the future. You'll find it at the following link: https://www.youtube.com/watch?v=oHiyHBO-4pk&feature=emb_title

Representative patents

- Patent US10049774, “Systems and methods for forming and maintaining a high performance FRC,” filed 23 March 2016, granted 14 August 2018, assignee: TAE Technologies, Inc.: https://patents.google.com/patent/US10049774B2/en?oq=US10049774
- Patent US 9924587B2, “Negative ion-based neutral beam injector,” filed 25 January 2017, granted 20 March 2018, assignee: TAE Technologies, Inc.: https://patents.google.com/patent/US9924587B2/en?oq=9924587
- Patent US10217532B2, “Systems and methods for merging and compressing compact tori,” filed 10 April 2017, granted February 26, 2019, assignee: TAE Technologies, Inc.: https://patents.google.com/patent/US10217532B2/en?oq=US10217532
- Patent US10438702, “Systems and methods for forming and maintaining a high performance FRC,” filed 16 July 2018, granted 8 October 2019, assignee: TAE Technologies, Inc.: https://patents.google.com/patent/US10438702B2/en?oq=US10438702
- Patent US10743398B2, “Systems and methods for forming and maintaining a high performance FRC,” filed 12 August 2019, granted 11 August 2020, assignee: TAE Technologies, Inc.: https://patents.google.com/patent/US10743398B2/en?oq=US10743398
- Patent EP3533068A1, “Systems and methods for improved sustainment of a high performance FRC elevated energies utilizing neutral beam injectors with tunable beam energies,” filed 30 October 2017, published 1 July 2020: https://patents.google.com/patent/EP3533068A1/en?q=tae+technologies&inventor=Michl+Binderbauer