The Fork in the Road to Electric Power From Fusion

Princeton Fusion Systems (PFS)

Peter Lobner, 1 February 2021

Princeton Fusion Systems was founded by Michael Paluszek and Stephanie Thomas in 2017 as a spinoff from its parent company, Princeton Satellite Systems. Princeton Fusion Systems is headquartered in Princeton, New Jersey. The firm's website is here: https://www.princetonfusionsystems.com

The Princeton Field-Reversed Configuration (PFRC) fusion project aims to develop small, simple, and clean fusion power generators in the 1–10 MWe class. The PFRC design has its foundation in over 15 years of research and experience at the Princeton Plasma Physics Laboratory (PPPL). The same basic fusion reactor design concept also is being developed as a direct fusion drive (DFD) for fusion-powered spaceflight.

The PFRC is described in Patent US2015/0294742A1.

> "The invention is for a …. deuterum-helium-3 (D-He3) fueled, steady state, small nuclear fusion reactor. The reactor employs a field-reversed configuration (FRC) magnetic confinement scheme and an odd-parity rotating magnetic field (RMFo) that produces periodic, co-streaming, energetic ion beams which heat the plasma. This is accomplished through radio-frequency (RF) heating, which can effectively heat and maintain the plasma."

The PFRC is designed for aneutronic D-He3 fusion, which occurs as follows:

$$D + 3He \rightarrow p + {}^{4}He + 18.4 \text{ MeV}$$

Most of the fusion energy (14.7 MeV) is carried by the proton (p).

The D-He3 reaction has the lowest energy threshold for an aneutronic fusion reaction, occurring a temperature of about 800 million °C. This is an intermediate temperature range between deuterium-tritium (D-T) fusion at about 100 million °C and aneutronic hydrogen-boron-11 (p-B11) fusion at about 3 billion °C. One problem with D-He3 fusion is the rarity of helium-3 on Earth.

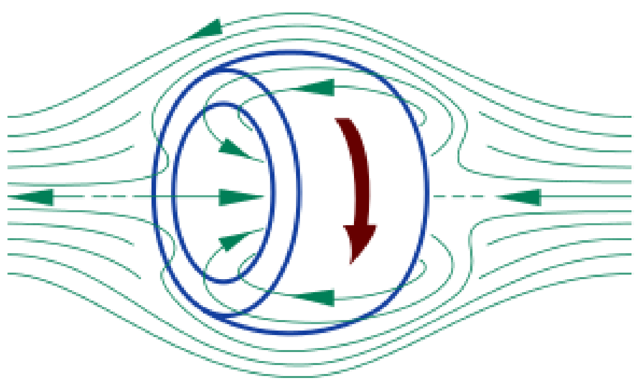
Stray D-D fusion reactions also will occur. One of the D-D reactions produces helium-3 and a relatively low energy 2.45 MeV neutron.

$$D + D \rightarrow n + {}^{3}He + 3.27 \text{ MeV}$$

In comparison, D-T fusion produces 14 MeV neutrons that require much more shielding. The second D-D reaction produces a 3.02 MeV proton and tritium.

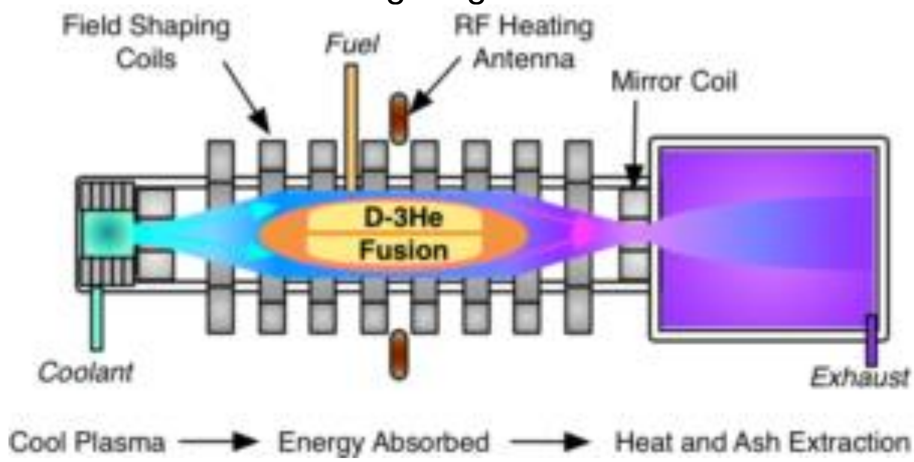
$$D + D \rightarrow p + T + 4.03 \text{ MeV}$$

The PFRC device is designed to create and compress a field reversed configuration (FRC) D-He3 plasma, which has the form of a self-stable, rotating plasma torus, similar to a smoke ring.



FRC: a toroidal electric current is induced inside a cylindrical plasma, making a poloidal magnetic field, reversed in respect to the direction of an externally applied magnetic field. The resultant high-beta axisymmetric compact toroid is self-confined. Source: Wikipedia

With the FRC plasma is formed in the center section of the PFRC device, plasma confinement is accomplished with a set of field shaping coils. The PFRC uses odd-parity rotating-magnetic-field (RMFo) heating to drive electrical current and heat the plasma to fusion temperatures as a stable, sustained plasma, while maintaining good energy confinement. The general arrangement of a PFRC device is shown in the following diagrams.



Source: PFS

More details are provided in Patent US2015/0294742A1, Figure 4.

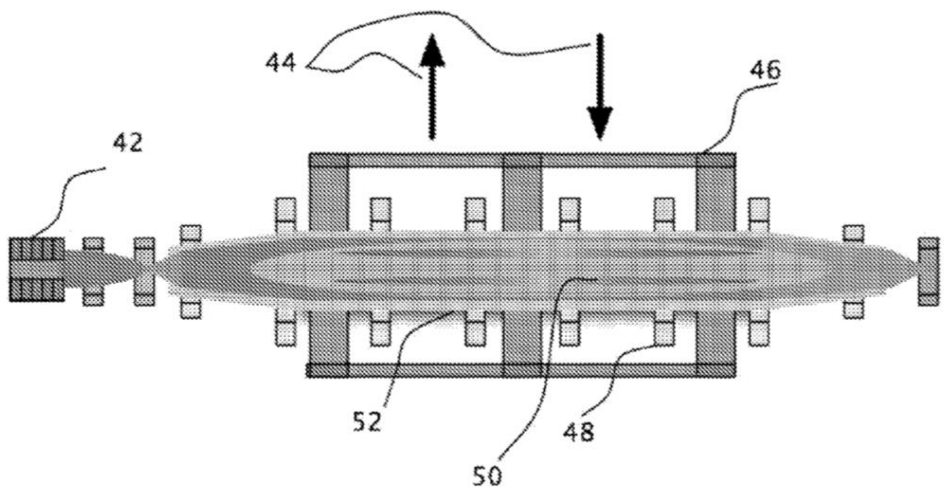


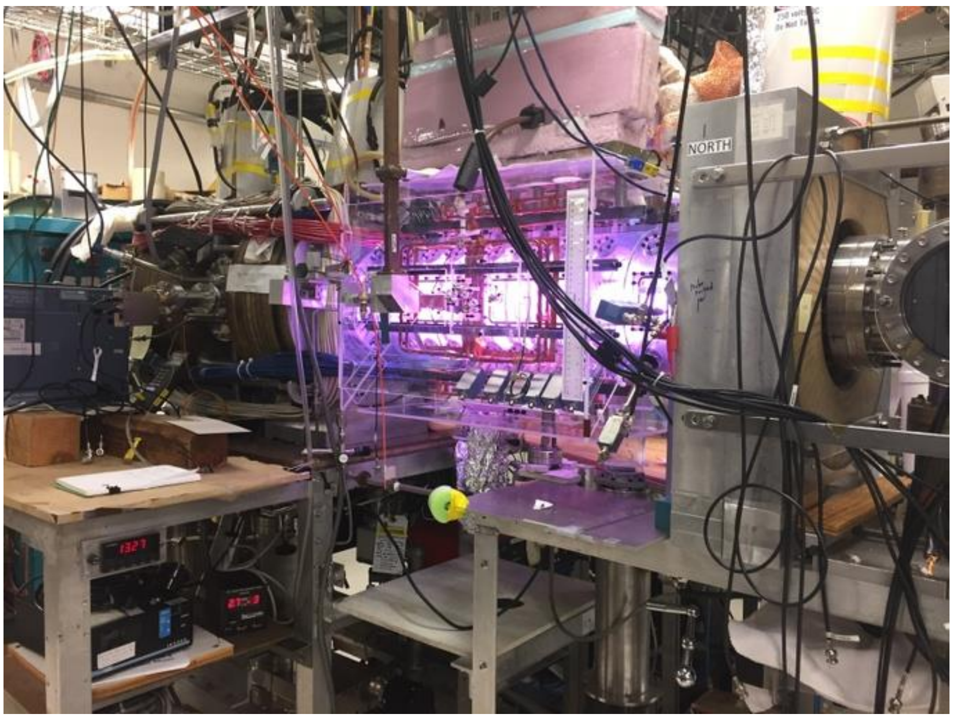
FIG. 4

Legend

42: Fuel injector
44: Anti-parallel components of the RMF_o field created by the RF antennas. The direction of the RMF_o is opposite on the two sides of the mid-plane of the reactor, hence the name odd-parity.
46: RMF waveguides and antennas
48: Axial flux coils
50: Internal structure of the plasma is defined by the field-reversed configuration
52: Radiation shield, for reflecting, attenuating, and absorbing, neutrons, Bremsstrahlung, and synchrotron radiation

Princeton Fusion Systems has developed two generations of PFRC machines:

- PFRC-1 has been operating since 2008 and has been used to demonstrate electron heating and achieved an electron temperature of 0.2 keV and density of 1 x 10^{18} electrons /m^3
- PFRC-2 has been operating since 2011 and has been used to demonstrate ion heating and achieved an electron temperature of 0.64 keV and density of 6 x 10^{18} electrons /m^3



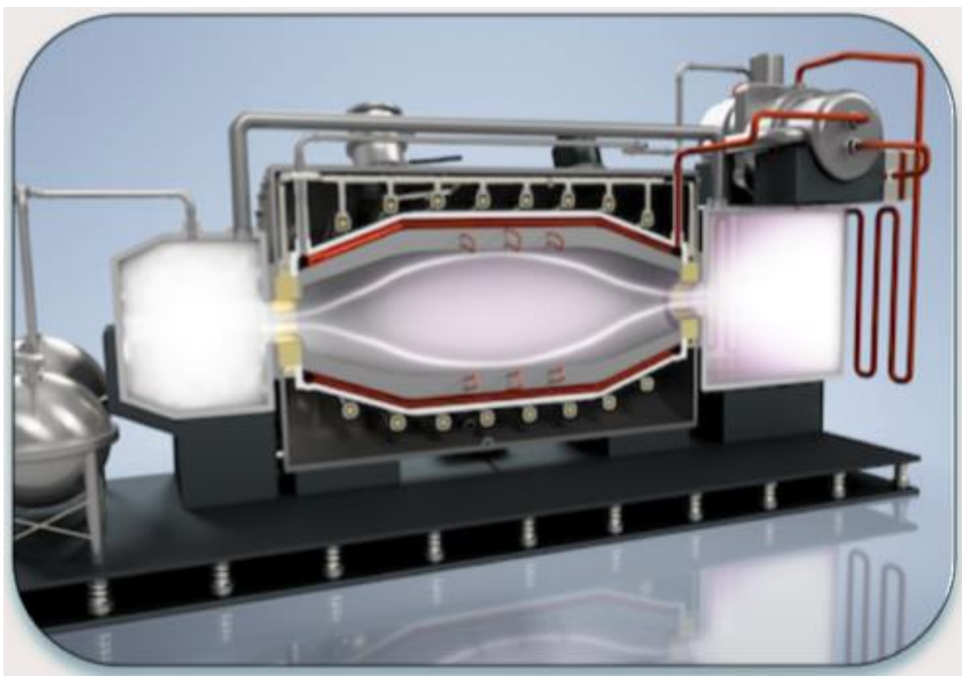
PFRC-2 machine. Source: PFS

On 18 January 2019, PFS received $1.25 million in DOE funding in a cooperative agreement awarded under the ARPA-E OPEN 2018 program. This “next-generation PFRC” funding is supporting upgrades to the radio-frequency power system and magnetic field strength, as well as the installation of new diagnostics to measure the temperature inside the upgraded PFRC-2.

In January 2021, PFS received a DOE-FES INFUSE grant “for installing an advanced diagnostic, constructed and operated by ORNL researchers, on the current phase of the PFRC to measure key features of the magnetic field. Such measurements are intended to indicate whether the method planned for forming the plasma will produce sufficiently hot and dense plasma to create fusion reactions." The goal of this work is to guide the optimization of the PFRC device.

Concept for a PFRC power plant

PFS plans to develop small, simple fusion power generators in the 1–10 MWe class. The general configuration is shown in the following diagram. At this scale, the reactor probably will be designed for mass production for widespread deployment as single units and as aggregated units in a larger power generation facility.



Source: PFS

Funding

Princeton Fusion Systems is primarily funded by DOE.

- January 2018: $1.25 million in a cooperative agreement under the DOE ARPA-E OPEN 2018 program
- September 2020: $1.1 million ARPA-E GAMOW program grant
- January 2021: DOE FES INFUSE grant

Private funding sources have not been identified.

For more information

- J. Bahmani, “Radiation effect of neutrons produced by D-D side reactions on a D-3He fusion reactor,” Radiation Effects and Defects in Solids, Volume 172, Issue 3-4, p.192-203, April 2017: https://ui.adsabs.harvard.edu/abs/2017REDS..172..192B/abstract
- “Next Generation PFRC,“ DOE ARPA-E OPEN 2018: https://arpa-e.energy.gov/technologies/projects/next-generation-pfrc

Patents

- Patent US2015/0294742A1, “Method, apparatus, and system to reduce neutron production in small clean fusion reactors,” filed 25 March 2013, granted 19 September 2019, assigned to Princeton University: https://patents.google.com/patent/US20150294742
- Patent US2015/0098543A1, “Method and apparatus to produce high specific impulse and moderate thrust from a fusion-powered rocket engine,” filed 10 May 2013, granted 21 November 2017, assigned to Princeton University & Princeton Satellite Systems, Inc.: https://patents.google.com/patent/US20150098543?oq=princeton+satellite+systems
- Patent 2015/0055740A1, “In space startup method for nuclear fusion rocket engines,” filed 22 August 2014, granted 12 March 2019, assigned to Princeton Satellite Systems, Inc.: https://patents.google.com/patent/US20150055740?oq=princeton+satellite+systems

Videos

- “Princeton Field-Reversed Configuration” (2:07 minutes), Princeton Satellite Systems, 20 November 2019: https://www.youtube.com/watch?v=C-CkJg5e130