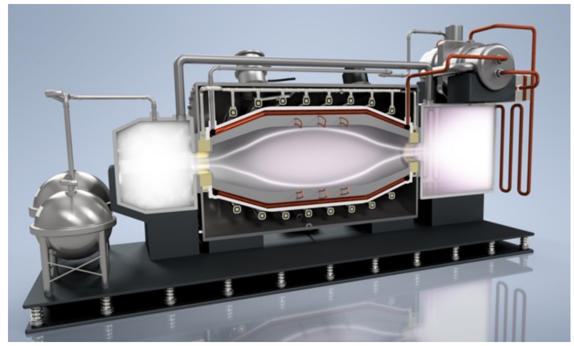
The Princeton Field Reversed Configuration:
A New Paradigm in Fusion Power



The Princeton Field Reversed Configuration (PFRC) Nuclear Fusion Reactor is a revolutionary approach to fusion power generation. Compared to other fusion reactor designs, PFRC reactors would be physically smaller and lower power, 1-10 MW, hence portable and suitable for a distributed power grid, the preference of power utilities. PFRCs would produce little radiation, about 1/1000 *per* unit of power of that by the mainline approaches to fusion power.[1,2] Low radioactivity greatly eases reactor design, maintenance, and licensing. These characteristics would enable rapid development at relatively low capital cost and initial use in niche applications such as for off-grid industrial installations, emergency power at sites of natural disasters or terrorist attacks, military forward power, and naval and space propulsion. DOE, NASA, and ARPA-E have funded early development.

The PFRC plasma is confined by a linear array of magnets and is heated by radiofrequency (RF) power. The predicted high plasma temperatures[3,4] and FRC characteristics enable the use of the advanced fuel mixture deuterium and helium-3 (D-^{3}He), reducing neutron production.[5,6] The small size further reduces neutron production, primarily due to the PFRC's unique ability to rapidly exhaust tritium ash, a valuable by-product of D-^{3}He fusion. Low radiation and FRC properties allow PFRCs to be completely fabricated with currently available materials and components. The simple geometry and small size of PFRCs drive the projected low cost of development and implementation.

Competing fusion concepts that would burn deuterium-tritium (D-T) fuel, primarily tokamaks and stellarators, suffer from high neutron production, hence require complex, expensive, and meter-thick lithium-bearing shielding systems and frequent in-vessel maintenance.[7] Low efficiency thermal cycles are used to extract fusion-generated power, most often of GW scale, from the required highly combustible and thick lithium shielding blankets of D-T devices. This lithium must also breed the tritium fuel, which does not exist in nature. The PFRC shielding would be boron ceramic, a chemically stable solid, and just 0.2-m thick. The geometry allows higher efficiency energy extraction.[8] Other FRC-based fusion reactor efforts are VC funded.[9] They face far more difficult physics and technology challenges than the PFRC in such areas as energy confinement and component lifetime.

PPPL developed the present research device, the PFRC-2, with grants from DOE. PFRC-2's goal is to demonstrate ion heating by RF. Its successor, the PFRC-3, would further raise the ion temperature and energy confinement time, each by factors of 10 or more. Following that, the PFRC-4 would achieve fusion power generation. Princeton Fusion Systems (PFS) has received grants from NASA for space applications and from ARPA-E for critical ion-heating demonstrations. PFS recently received an ARPA-E grant to develop more efficient power electronics needed by PFRCs, the broader fusion power industry, and others.

Though helium-3 is relatively scarce, there is sufficient helium-3 for emergency, military, and space applications. Additional helium-3 can be generated using deuterium-fueled breeder reactors or *via* extraterrestrial mining.[10] Note that many tokamak designs are also considering using helium-3 to enhance RF heating..

PFRC: Small, Simple, Clean

The PFRC is small, with a plasma radius of just 0.25 m and a length near 2 m. Power plants of this size are portable. The size is intimately related to underlying physics processes, one being exhaust of the fusion ash products by cooling and entrapment in a flowing cool plasma outer layer. PFRC reactors cannot be made considerably larger in radius without compromising their cleanliness and stability. The small radius requires RF heating, a technique more reliable and with better developed components than neutral beam heating, the latter favored by proponents of larger fusion reactors. PFRCs can be configured for a range of power levels by adjusting the length. PFRC modules of 1-10 MW can readily be added to or removed from a particular site to suit its evolving needs.

The geometry of the PFRC is linear, consisting of an array of coaxial magnets, as shown in Figure 1. There are no interlocking or unusually shaped magnets as required in donut-shaped tokamaks and cruller-shaped stellarators, respectively. PFRCs require a magnetic field strength already available in commercial superconducting magnets, being similar in size and field strength to those used in current MRI machines. This synergy will drive down the cost of the magnets. No expensive and lengthy magnet development program is needed.

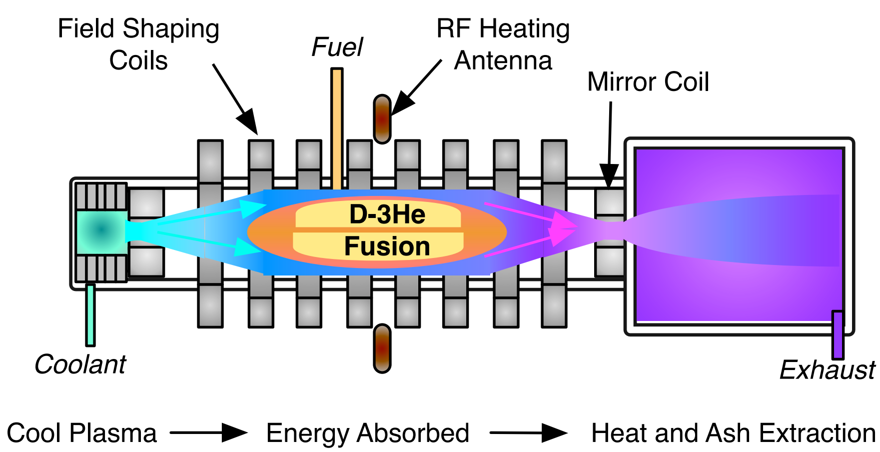


Figure 1. Schematic of the PFRC. Cool plasma flows from left to right around the fusion region, absorbing the power and transporting the ash to the extraction region.

The RF equipment for plasma heating and current drive can take advantage of recent developments in solid-state amplifier technology, reducing size and cost while producing several 100 kWs of power.

The minimum research goal for PFRCs is a plasma whose ions have reached fusion-relevant temperatures and densities. Once the associated physics has been demonstrated, designing a commercial reactor is an engineering exercise. We intend to heat ions to 1 keV in PFRC-2, which is an initial proof-of-concept of the physics. Heating ions to 5 keV in PFRC-3 would follow, to test important aspects of the technology and the physics in a higher temperature regime. 5-keV ions are considered the fusion benchmark and would provide full viability of the PFRC approach.

D-^{3}He reactors, with their superior cleanliness and safety, can be used in proximity to densely populated and sensitive places including submarines, emergency power generation in hospitals, military vehicles and encampments, and cities. The low weight of the thin shielding required in PFRCs is an important reason that these reactors are suitable for applications in space.

Initially, the number of PFRC reactors will be limited to ~ 100 by availability of ^{3}He, a rare element with several valuable markets. To overcome this limitation, a class of ^{3}He-catalyzed D-D fusion PFRC reactors using the same configuration and heating technology is possible.[11] Though less clean than D-^{3}He reactors, only seawater is needed for fuel. This will increase terrestrial power generation applications and could, one day, provide baseload power.

PFRC Innovations

1. Odd-Parity RF plasma heating and current drive

PFRC is built upon the innovative radiofrequency (RF) plasma heating and current drive technique termed *odd-parity rotating magnetic fields*, RMF_o. This refers to the geometry of the RF antenna used. The antenna, placed outside and encircling the plasma, generates a time-varying magnetic field on each side of the plasma's axial midplane. This magnetic field has the same parity – the same mirror symmetry – as the FRC itself. With antenna and its magnetic field symmetries identical to the FRC's, closed field lines in the FRC region result, increasing confinement time – a critical metric to allow the hot ions enough time to fuse.[12] FRCs driven with even-parity antenna failed to produce good confinement.

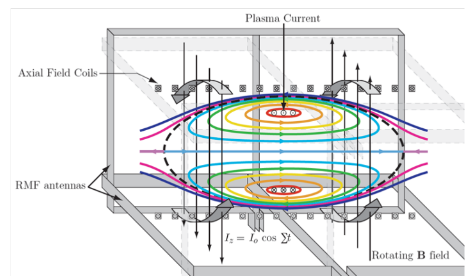


Figure 2. , Odd-parity RF heating creates closed field lines, improving the plasma confinement

The frequency of the RF heating is specially selected to heat ions, especially the ^{3}He ions. Keeping the ^{3}He ions hotter than the D ions would further reduce neutron production. In a PFRC, ions are accelerated by an azimuthal electric field generated by the time-varying RMF_o. In addition to heating the plasma, the RF drives plasma current essential for sustaining the plasma's shape and has also seen to improve stability.

2. D-^{3}He fueled with Intrinsic Tritium Removal

Advanced fuels for fusion reactors are those which create fewer neutrons than D-T, the fuel mixture which burns at the lowest plasma temperature. The three advanced-fuel mixtures considered possible are p-^{11}B, D-^{3}He and D-D. Here we discuss two aspects of D-^{3}He. Other aspects of D-^{3}He and ones of p-^{11}B and D-D are described later.

Though D-^{3}He fusion produces no neutrons directly, unavoidable D-D fusion also takes place. This produces T which would quickly fuse with the plasma's D and generate neutrons that damage and activate materials and are harmful to humans. The PFRC's small size compared to the fusion-produced T^+ gyro radius (radius of motion of the particle around the field lines) *naturally* allows the energetic T to be exhausted rapidly, in a few ms.[13] The process is akin to the drag that causes a satellite to decelerate as it enters the earth's atmosphere. In the PFRC, the T decelerates in a cool flowing plasma layer outside the FRC core, Figure 3. Once in that layer, the T moves away from the core, hence does not fuse.

If D-^{3}He is such a good fuel, why could tokamaks not use it? Among the numerous reasons are: 1) tokamaks are big, producing GWs of power. A single 1-GW tokamak would consume all the terrestrially available ^{3}He (each year) in 5 weeks, hardly enough time to make the capital investment worthwhile, let alone learn how to control the fusion process; 2) D-^{3}He releases all its energy as charged particles. The resulting heat flux on the tokamak divertor plates exceeds that tolerable by about an order of magnitude; 3) because D-^{3}He fusion requires a 10x higher ion temperature than D-T, a 3x stronger magnetic field is needed, well beyond even high-temperature superconducting magnet technology; and 4) the large tokamak size does not allow rapid removal of the T formed by one D-D fusion branch. Neutrons are then formed by D-T fusion at nearly the same rate as for pure D-T burning devices, largely negating the benefit of ^{3}He.

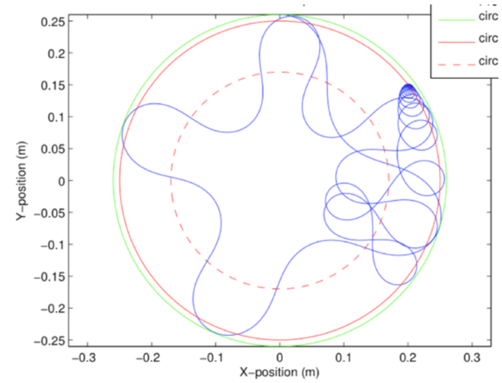


Figure 3. Tritium gyro radii initially cross in and out of the cool outer plasma layer, causing them to lose energy until they are captured by the layer's field lines and exit the engine. (M. Chu-Cheong)

3. High efficiency power and propulsion

As noted above*, via* "standard" low efficiency thermal processes, D-T reactors extract and convert to electricity the fusion energy deposited in the meter-thick neutron-absorbing blankets outside the plasma. The primary reason for this, *i.e.,* extracting the fusion energy from the blanket, is that 80% of the fusion energy produced by D-T is in the form of neutrons which are absorbed in the blanket. Standard thermal processes, those possible with Li-bearing blankets, have an efficiency near 30%.

Advanced fuels release most of their fusion energy as charged particles. The remainder is released as photons. Both energy loss channels allow direct energy conversion, providing efficiencies above 60%. For space propulsion applications, the charged particles themselves can be used as propellent, hence the name "direct fusion drive (DFD)" applied to our rocket engine concept. The rocket engine does not require an intermediary inefficient electricity production step.

4. The proper size and shape

A critical aspect of the PFRC design is its relatively small size. This size was chosen for several reasons. Firstly, it is all that is needed for net power production because the energy confinement in FRCs is "classical", about 10x better than the best attainable in tokamaks, "neoclassical". Secondly, the small size – defined as when the fuel ion gyro radii are comparable to the plasma size – places the plasma in the kinetic regime, not the instability-prone fluid regime. Thirdly, a small size fits well into a sound business plan, requiring less capital investment and opening niche applications for which the cost of electricity is far less important than when competing in the consumer electricity market.

The question is often asked, why can the PFRC be so small compared to tokamak reactor designs? Consider the triple product of the plasma density (n), energy confinement time (τ), and temperature (T), $n\tau T$, the commonly used figure-of-merit for fusion. This can be related to device properties by the equations for energy confinement time and plasma β, the ratio of the plasma pressure to the magnetic field energy density,

$\tau = a^2/X$, where X is the plasma's thermal conductivity and a is the plasma's radius,
$\beta = 8\pi nT/B^2$.

Combining these yields the triple product,

$$n\tau T = (B^2a^2)\ (\beta/8\pi X).$$

To achieve high $n\tau T$, tokamak proponents choose to increase the first factor, a (ITER) and B (SPARC/ARC), both expensive. FRCs, however, naturally have 20 times greater β than tokamaks (1 vs 0.05) and 10 times smaller X (classical heat transport *vs* neoclassical). Operating at the same B, FRCs can have a factor of 14 smaller radius. It is important to note that donut- (or cruller)-shaped plasmas – true toroids with "holes" along their major axis and the inner legs of magnetic coils threading through that hole – have higher magnetic field at the inner legs of their magnets than at the plasma's minor axis; in contrast, solenoidal plasmas, like FRCs, have the same (maximum) magnetic field strength on their axis as at the coils, further increasing the attractiveness of FRCs.

We note that for the small PFRC to operate in steady state, not as a pulsed power source which faces severe cyclical stress problems, necessitates RF heating instead of compression or energetic beams, the latter which would pass through a small plasma.

Again, FRCs have no magnets on the plasma's inboard side, the aforementioned "hole," while stellarators and tokamaks do. Both inner and outer legs of stellarator and tokamak magnets need shielding from the neutrons. The net thickness of their shielding is greater than 4 m across the diameter while only 0.4 m for a PFRC.

Assessment of the Competition

There are several well-publicized VC-backed fusion companies: General Fusion (GF), TAE Technology, Helion, Commonwealth Fusion Energy (CFE), and Tokamak Energy (TE).

The D-T burning groups, CFE and TE, aim to develop tokamak reactors. They face two enormous tritium technology problems: breeding (and extracting) T and developing neutron resistant materials. No credible solutions for how to solve these problems have been tested or even proposed. Moreover, these two companies describe GW-size fusion reactors, requiring large capital investment and protracted licensing endeavors. We noted that tokamaks have thick shielding and low β, hence use their expensive magnetic field inefficiently. (Because of the spatial variation of the quantities that define β, a volume-average of β is often specified.)

There are university and national lab efforts to explore D-T stellarators as fusion reactors. The largest presently operating stellarator, the W7X in Germany, took over twenty years longer than first announced intended to build, largely due to the complexity of the magnet coils required to generate the cruller-like fields. W7X's size is comparable to tokamaks operating in the 1970's. Based on this, one could estimate 50+ years to get to the ITER scale and an additional century to produce power for the grid. Stellarators would face the same unsolved neutron problems as tokamaks.

The two FRC-based efforts, TAE and Helion[14], recently received billion-$ levels of financial support from VCs. The TAE effort focuses on 4-m-plasma-diameter, 0.5-1 GW, p-^{11}B-fueled, beam-heated, steady-state reactors; the Helion's design is for 0.05-m-plasma-diameter, 0.1-0.5 GW, D-D fueled (He^3-catalyzed), compression-heated, pulsed reactors. p-^{11}B is unlikely to provide net energy gain for three reasons: 1) the energy released *per* fusion reaction is about 1/2 that from D-^{3}He or D-T fusion; 2) p-^{11}B fusion requires a higher plasma temperature than D-^{3}He, increasing the energy loss by radiation; 3) for the same plasma electron density, the product of the fusing-ion densities, which sets the fusion power, is 4 times lower than D-T's. The net result is an 8-fold drop in fusion power. No scheme for solving this poor energy balance problem has been described.

The D-D approach supported by Helion has no way to remove the T ash. When the inevitable D-T fusion occurs, damaging neutrons are released causing the same materials problems as in D-T tokamaks. A Helion reactor would be pulsed at 1 Hz, 3 x10^7 pulses in each year. Severe stress problems would arise.

None of the VC fusion companies have technology that can produce a reactor as small as 1 MW or even 10 MW. In that sense, the competition for the PFRC is small fission (anything under 200 MW, down to 3-5 MW), and diesel and propane generators. Small fission does not solve the complex problems of radioactive fuel and proliferation issues, radioactive waste, nor the low overall efficiency of fission requiring large volumes of wastewater. Diesel and propane generators require logistics pipelines of fuel and produce fossil fuel emissions. PFRC would solve these problems by providing an energy source that does not need to be refueled throughout its 30-year design life.

A Chinese energy company, ENN, has built a copy of the PFRC, and may be working towards a 1 to 10 MW class fusion reactor and is working on other compact fusion device designs.[15]

PFRC Fusion Reactor Business Model

Small PFRCs could be manufactured in a single plant and shipped, completed and fueled, to a customer or site. The end business model is "pay per unit". Service contracts would provide additional revenue streams. We envision a minimum of two models, likely 1 MW and 10 MW, which may utilize the same magnet design but differ in length. The revenue plan is to first pursue a high-value space or military application for a full-scale prototype, expecting $25M profit on a $500M contract. Additional space or military units, from 1 to 10 per year, would provide $5M profit on $100M units. Civilian commercial units would then become available at about $50M per 10 MW ($0.02/kWh over 30-year reactor lifetime). The first use of fusion reactors by NASA and the military, preceding consumer applications, follows the example of Admiral Rickover when he developed the US's nuclear navy. The benefits of military testing cannot be overstated.

Intellectual Property

Four US patents have been granted for the PFRC technology and four in process:

1. Method to Reduce Neutron Production in Small Clean Fusion Reactors, #9,767,925
2. Method to Produce High Specific Impulse and Moderate Thrust from a Fusion-Powered Rocket Engine, aka "Fusion-Powered Rocket Engine", #9,822,769
3. In Space Startup Method for Nuclear Fusion Rocket Engines, #10,811,143
4. Fueling Method for Small, Steady-State, Aneutronic FRC Fusion Reactors, #10,811,159

Team Leadership

PFRC inventor Dr. Samuel Cohen has over 40 years of experience as a plasma physicist. Between 1988-1994 he worked on ITER then focused on the unique properties of FRCs. He has been on the faculty of Princeton University since 1985 and on the PPPL research staff since 1973. For over 30 years, he has served as the director of Princeton University's Program in Plasma Science and Technology and for a dozen years was the associate editor of *Physics of Plasmas*. Since 2011, he and Princeton Satellite Systems have collaborated on PFRC research and c commercialization.

Princeton Satellite Systems (PSS), *aka* Princeton Fusion Systems, was founded in 1992 and develops advanced technology for the aerospace and energy sectors.

Mr. Michael Paluszek founded PSS after working as a Guidance, Navigation, and Control engineer at GE Astro Space and Draper Laboratory. PSS sells commercial software for satellite control design and performs research for the government, including SBIRs with NASA, Army, Navy, Air Force, NSF, and MDA. Mr. Paluszek is the Principal Investigator for a NASA STTR on the PFRC's Radio Frequency heating system and two ARPA-E awards, our OPEN 2018 award for PFRC development and a GAMOW on power electronics for fusion systems.

Ms. Stephanie Thomas was the Principal Investigator for the NASA NIAC contract on a PFRC-based Pluto orbiter and lander mission, as well as on a NASA STTR on the superconducting magnet subsystem. She is the Vice President of PSS and has been with the company since 2001.

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