The Princeton Field Reversed Configuration (PFRC) for Compact Nuclear Fusion Power Plants

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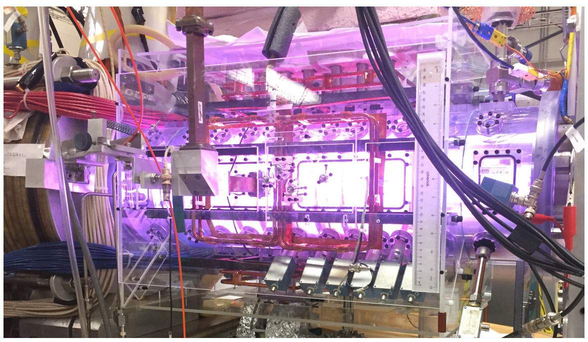
Abstract. The Princeton Field-Reversed Configuration (PFRC) nuclear fusion reactor concept is an innovative approach to fusion power generation prioritizing low neutron production and small size. Mathematical analysis shows that the novel heating approach generates an FRC with closed field lines. Simulation data from a single-particle Hamiltonian code predicts ms-scale plasma heating in reactors while PiC codes predict the formation of warm FRC plasmas from initial mirror fields. The PFRC-1 and PFRC-2 experiments have heated electrons to energies well over 100 eV and plasma durations to 300 ms, more than 10^4 times longer than the predicted tilt instability growth time. From these data, we have created a development plan and anticipated performance metrics for a fusion reactor based on the PFRC concept. The PFRC-2 experiment is designed to demonstrate ion heating. Measurements are expected to be available from a newly constructed charge exchange diagnostic once it is deployed.

The resulting 1-10 MW PFRC reactors would be suitable for diverse applications, from submarines to urban environments to space propulsion. They would provide a firm, carbon-free power source for distributed and modular power plants of the future. PFRC is a steady-state, driven magnetic confinement concept. The small size of the planned reactor enables a rapid exhaust mechanism for the tritium ash. Low radiation from advanced fuels makes the reactor safer to operate and, in combination with the simple geometry and small size, should dramatically lower development and maintenance costs. No new materials or superconducting coils are needed for a power reactor.

Keywords: nuclear fusion, field-reversed configuration, magnetic confinement fusion, modular power, space propulsion

1. Introduction

PFRC is a novel reactor class. As described later, it would use only one RF system, odd-parity Rotating Magnetic Field (RMF_o), to drive plasma current, heat the plasma, improve confinement, and provide stability. PFRCs would burn deuterium and helium-3, ($D-^3He$), a fuel mixture that generates little radioactivity. The relatively small machine will promote rapid exhaust of the tritium produced by D-D side reactions, further reducing the neutron wall load. Electricity would be produced using a Brayton cycle with a helium/xenon working fluid and thermalization of X-ray and synchrotron radiation emitted from the plasma. The machine is intended for compact, mobile, and modular applications, including space propulsion.[1, 2, 3] For military forward power, a 1-MW PFRC could be mounted on an HEMTT truck, as shown in Figure 1b. The PFRC-2 experiment is operating at PPPL.



PFRC-2 plasma shot with H_2

Model of truck mounted 1 MWe PFRC.

2. Status of development: The PFRC-2 Experiment

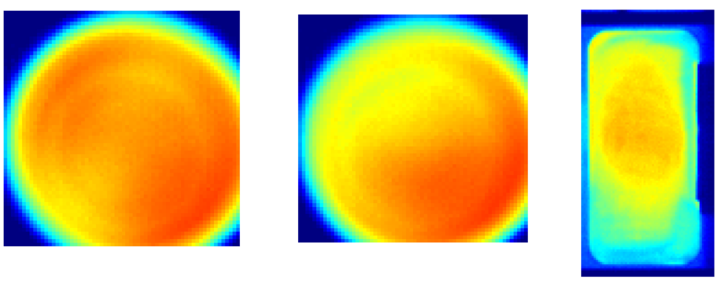
RMF_o current drive was first demonstrated in the 4-cm plasma radius PFRC-1 experiment in 2006.[4] Experiments are ongoing with the second-generation machine, PFRC-2, which has a flux conserver inner radius of 8 cm (Figure 1a). Results from experimental studies of electron heating in PFRC-2 have surpassed theoretical predictions, with minority electron populations reaching temperatures of 500 eV, maximum energies exceeding 1.5 keV, and pulse lengths up to 300 ms, though typically 10 ms. PFRC-2 has operated with RF frequencies from 4.3 to 12 MHz, forward power up to 100 kW, (central) vacuum magnetic fields of 350 G, and mirror ratios of 30. The coupling efficiency of RF power to the plasma has reached 60%.

PFRC-2 is being upgraded to operate with an RMF frequency of 2 MHz, a compressed magnetic field of up to 0.1 T, and a total RMF forward power of 200 kW. This will result in an RMF field strength of up to 15 G. At these parameters, single-particle simulations predict explosive ion heating to energies above 1 keV.[5] Table 1 gives the latest results and the targets for both PFRC-2 and future machine generations. Fast camera images and the stripping cell analyzer are shown in Figure 2a and Figure 2b.

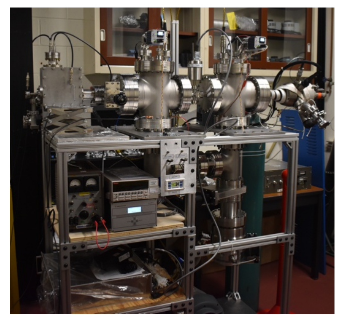
The next step for PFRC-2 will be the attachment of the Stripping Cell Ion Energy Analyzer that will measure ion temperatures.[6] These experiments are planned for the spring of 2024. To support the ion heating experiments, the RMF power will be increased from 140 kW to 200 kW. Belt coils will be added to double the axial field strength. Using better shielding, most of the noise that was plaguing the SDDs has been eliminated. During RMF with He, we have seen individual X-rays at energies up

Table 1: PFRC-2 experimental results and PFRC-3 and PFRC-4 targets.[5]

Parameter	PFRC-2 Value	PFRC-3 Goal	PFRC-4 Goal
Pulse length	300 ms	1 s	100 s
Magnetic field strength	to 350 G (vacuum)	1 T	6 T
Plasma temperature		10 keV	100 keV
Observed	100 eV e^- at 4.3 MHz		
Goal	500 eV ions at 2 MHz		
Plasma radius	8 cm	16 cm	25 cm
Plasma Density	1×10^{13}/cc	1×10^{14}/cc	4×10^{14}/cc
Fuel	H_2	H_2	D-^{3}He
τ_E (s)	5x10^{-5}	0.004	0.4



Fast camera images of PFRC-2. From left to right: m=2 rotational mode, axial view, m=1 rotational mode, axial view, stable radial. Credit: Liam David



Stripping cell ion energy analyzer constructed at PPPL with ARPA-E funding

to 2 keV, at brightnesses about 1×10^{-4} below those at 200 eV.

3. Commercialization

PFRC reactors would be manufactured in a factory. Current Overnight Capital Cost (OCC) estimates are $8.9M for a 1 MWe reactor and $24.5M for a 10 MWe reactor. This is based on current costs for superconducting magnets and similarly sized gas turbines, specific staff and facility size assumptions, and a production of 20 engines per year. A higher power output is achieved by building a longer PFRC. The magnet costs have a favorable scaling with higher power as strong mirror magnets are needed regardless of reactor length. The turbine costs scale nearly linearly with the engine power. PFRC has potential for space, undersea, and surface applications. Civilian requirements are emergency power, remote power, and power for remote industries. In the long term, after demonstrating the reliability, safety, and robustness of the PFRC in high-value space or military units, we would develop a commercial reactor design. We have used established methods to estimate the future levelized cost of electricity (LCOE) of a commercial plant. This requires addressing the cost and availability of helium-3.

Currently, helium-3 can be commercially produced from natural gas extraction and CANDU fission reactors. Helium-3 may in the future be sourced from breeder fusion reactors or lunar or planetary mining. Costs can be estimated from today's market or an assumed cost of the breeder reactor or planetary mining system. We assume a terrestrial spot price of ^{3}He of \$2000 per liter, or \$15M per kg, while deuterium is about \$14,000 per kg. A D-D breeder reactor system will consume 5 deuterium for every helium-3, which reduces the fuel cost by a factor of over 300 compared to the terrestrial helium-3, but has higher investment costs (OCC and fixed O&M for the additional reactors). Planetary mining may reduce the fuel cost by 1/15 compared to the spot price, where all the mining investment is assumed to be absorbed in the price. With appropriate regulatory changes to reduce staff compared to fission plants, and therefore operations and maintenance costs, we estimate modular plants using 10 MW PFRC units might achieve a LCOE of \$0.15/kWh with planetary helium-3, half the current cost of electricity in California, and \$0.22/kWh with bred helium-3.

4. Engineering of Large Projects

A fusion reactor is a complex system composed of numerous subsystems. Figure 3 shows a subsystem breakdown for a PFRC reactor. Each of the blocks is complex.

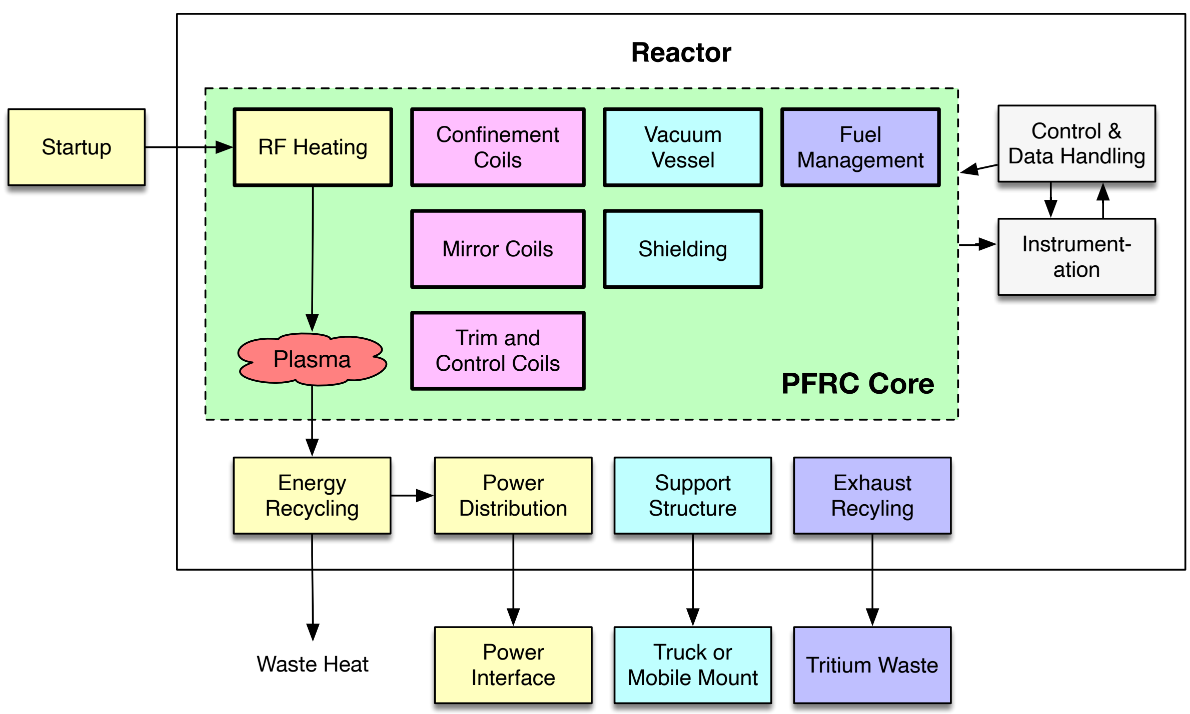


Figure 3: PFRC Subsystems

Complex engineering projects are time-consuming and progress is never linear. Table 2 gives selected engineering projects with information about their duration.

The F-35, Falcon-9, Boeing 787, and GPS IIR were based on well-developed existing

Table 2: Duration of Complex Engineering Projects

Project	Type	Start Date	First Product	Time (Years)
F-35	Aircraft	1995	2015	20
James Webb	Spacecraft	1996	2021	25
W 7-X	Plasma Experiment	1994	2014	20
ITER	Fusion experiment	2006	2025+	19+
NuScale	Small Modular Reactor	2002	2030 (projected	28
Falcon 9	Launcher	2005	2010	5
Boeing 787	Aircraft	2004	2011	7
GPS Block IIR	Spacecraft	1989	1997	8

technology by companies with strong track records. One of the co-authors of this paper was the lead attitude control engineer on GPS Block IIR. The shortest development time was for the Falcon 9. The NuScale SMR is a fission reactor that has an added regulatory burden. GPS IIR was based on operational GE Astro Space spacecraft.

5. Fusion Reactor Funding and Investment

Two important metrics are used to determine the value of an investment. One is the Compound Annual Growth Rate (CAGR) which gives the geometric progression ratio that provides a constant rate of return. CAGR is defined as

$$\mathrm{CAGR}(t_0, t_n) = \left(\frac{V(t_0)}{V(t_n)}\right)^{\frac{1}{t_n - t_0}} - 1 \tag{1}$$

$V(t_0)$ is the initial value, $V(t_n)$ is the end value and $t_n - t_0$ is the number of years. This assumes that PFRC is feasible and results in a product that generates revenue The revenues can be calculated based on the availability of helium-3. Current sources have sufficient helium-3 for a maximum of 100 MW per year. If helium-3 can be extracted from natural gas, this could be up to 1.5 GW/year. Assume a 1 MWe machine that costs $8.9M per machine. Assume that sales follow a logistic function with saturation after 12 years. This results in the CAGR shown in Figure 4. If we assume a price-to-earnings ratio (P/E) of 16 the company would be worth USD $60B at the end of the period. A P/E ratio of 16 is standard for technology companies. If the production of helium-3 saturates, then the market becomes a replacement market once the 1,500 1 MWe machines for which there is fuel are sold. This can be shifted in time should the first machines not arrive in 2032.

The next important metric is the present value [7]. The formula is

$$p = \sum_k \frac{s_k c_k}{(1+a)^t} \tag{2}$$

where c_k is the cost or income of stage k and t is its duration. s_k is the probability of moving to that stage which is the product of the probabilities of all previous stage

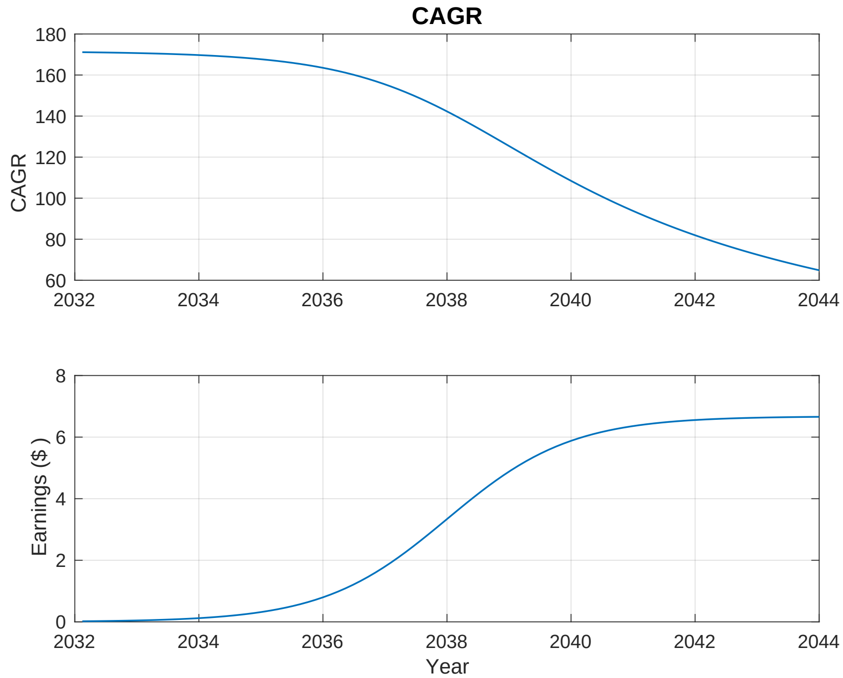


Figure 4: Estimated CAGR for PFRC assuming $8.9M machine cost.

transitions. This is the current value that one assigns to an investment. In this case, much like in the drug development part of the pharmaceutical industry, a probability has to be assigned to each stage in the development process. Assume that the probability of going from PFRC-2 to PFRC-3 is 1, but there is only a 0.2 probability of PFRC-3 being successful. If it is successful, the probability of going from PFRC-4 to prototype is 0.95 and the probability of going from prototype to production is assumed to be 0.98. It is not 1.0 because other factors (such as the discovery of a better power source) must be considered. This results in a present value of $1.8B if the profit is $2M per machine.

6. PFRC Development Plan

Figure 5 shows the development plant including spin-offs. Subsystem development is shown along with the expected regulatory burden. As noted above fusion reactor development spin-offs are critical in providing returns to investors. Virtually every technology shown in Figure 3 requires substantial improvement to support practical and economical power plants. As noted the RMF heating system requires high efficiency and reliable power electronics. This led to the ARPA-E GAMOW contract for developing high bandwidth power electronics for fusion reactors. The areas of development include RF heating, high current pulses, high voltage power supplies, and pulsewidth modulation circuits for plasma control. Figure 6 shows work done by PFS and Princeton University [8].

The diagram shows commercial spin-offs. Power Electronics is already a PFS commercial spin-off. Spin-offs are a critical part of fusion reactor development since they

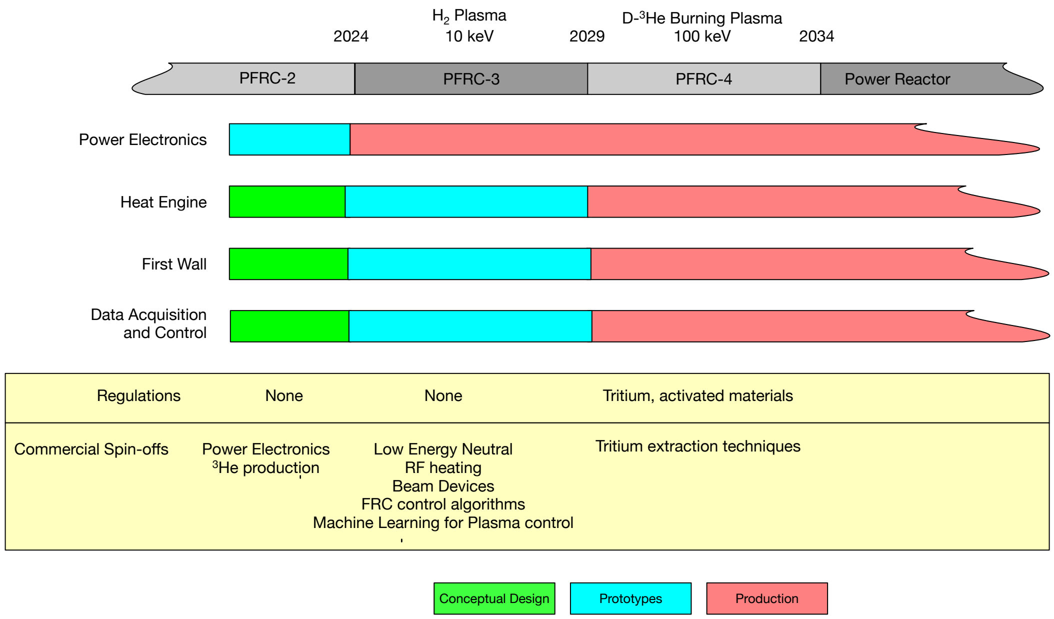


Figure 5: Development plan.

produce a return on investment for early investors. Fusion developer TAE spun off TAE Power Solutions which is focused on e-mobility. TAE Life Sciences is commercializing proprietary neutral beam technology for medical applications.

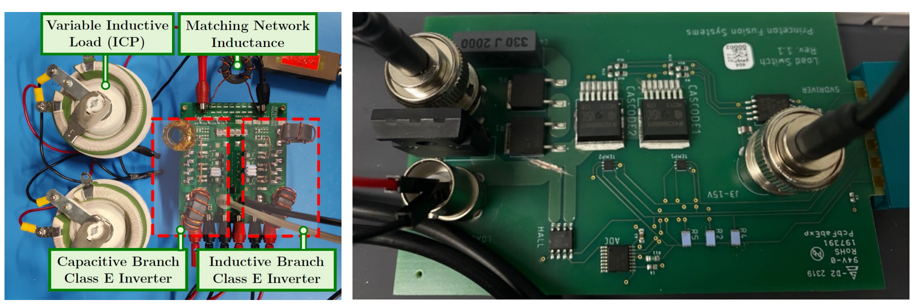


Figure 6: Electronics prototypes built under ARPA-E GAMOW. A Class-E amplifier is on the left. A load switch is on the right.

PFRC will be built by subcontractors and integrated by PFS. The power electronics will be designed by PFS and built with the same supply chain as was used in the ARPA-E GAMOW project. The core IP is in the fusion reactor itself. The subsystems are not a compelling selling point for investment. It is not feasible to develop the level of expertise needed to build combined cycle power plants, vacuum vessels, and superconducting coils. This allows PFS to stay agile and lean. It also gives PFS the flexibility to change subcontractors if needed. The total expected cost through PFRC-4 of $140M is due to the small size of the machine. PFRC-3 is a go/no-go point. If successful, PFRC-4 could be built quickly as it is only slightly larger.

7. Summary and Next Steps

PFRC has the potential to produce a new class of modular fusion power reactors for a wide variety of applications. Results with PFRC-1 and PFRC-2 show great promise. The next machine, PFRC-3, will be needed to deepen understanding of the plasma physics of the device at fusion-relevant plasma temperatures, magnetic fields, and plasma pressures, and to test technical methods. Such considerations include efficient RMF coupling to the plasma, particle, and energy transport and energy extraction. Widespread use of PFRC will require new sources of helium-3 which may be from natural gas extraction, CANDU fission reactors, helium-3 breeding, lunar mining, or from the gas giants.

8. Acknowledgements

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