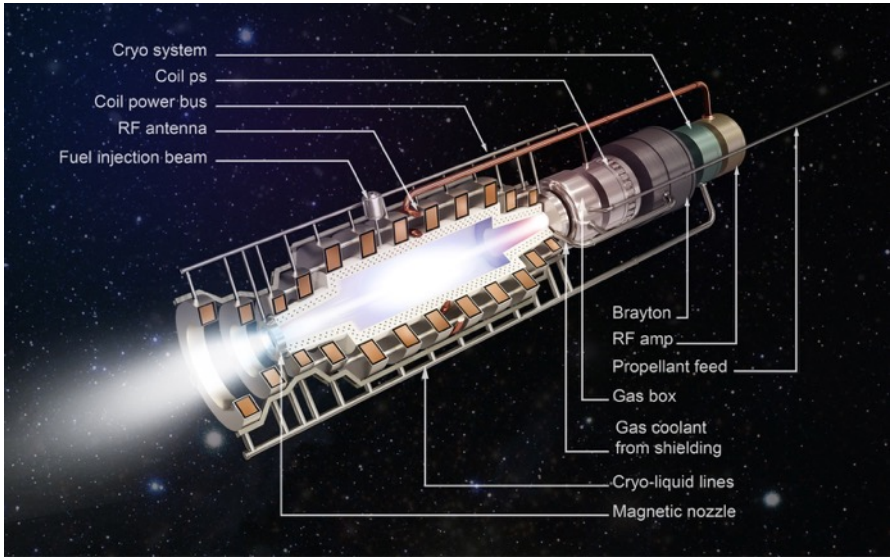
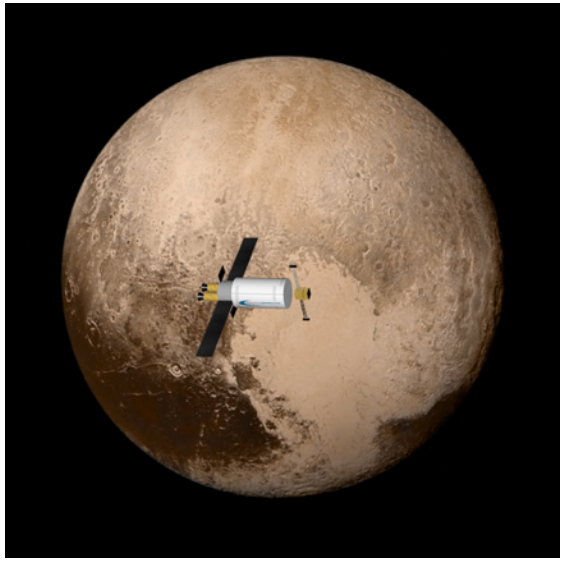
Direct Fusion Drive:

Enabling Rapid Deep Space Propulsion

Presented by: Stephanie Thomas

DIRECT FUSION DRIVE





FISO Telecon 05-29-19

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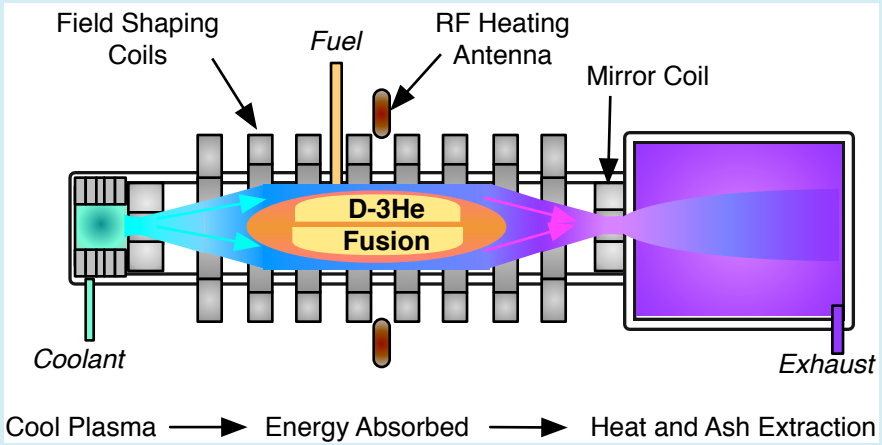
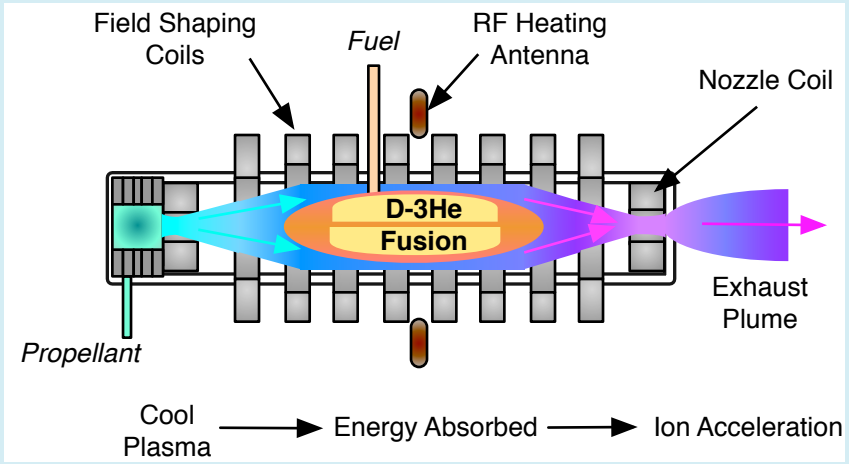
This material is based upon work supported by NASA under award No. NNX16AK28G and 80NSSC18K0040

DFD vs. PFRC





PFRC: Princeton Field-Reversed Configuration

- Compact toroid configuration
- RF heating
- FRC "in a mirror"
- SOL flow removes fusion exhaust

DFD: Direct Fusion Drive

- PFRC with an open end
- SOL flow rate adjusted to produce desired thrust and Isp
- "thrust augmentation"
- *Power* **AND** *Propulsion* in one device

Why Build a Small, Clean, Fusion Reactor?

PFRC will produce 1-10 MWe per mini-van size reactor, with almost no radiation.

Civilian

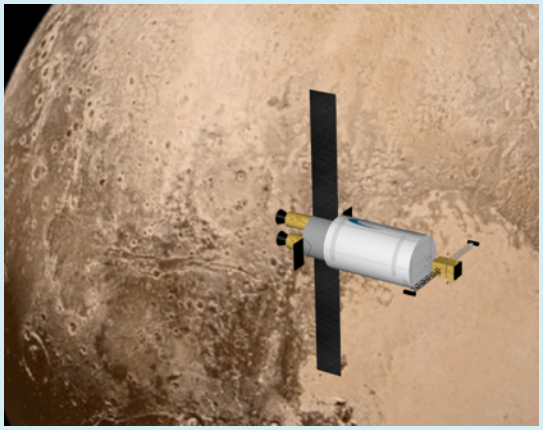
- Distributed and remote power
  - Villages in Alaska
- Mobile and emergency power
  - Hurricane damage, ex. Puerto Rico
- Modular power
  - Low capital cost power plants

NASA and DoD Space

- Deep space robotic missions
- Lunar/Mars settlements
- Asteroid/comet intervention
- Space platform power
- High power communications satellites

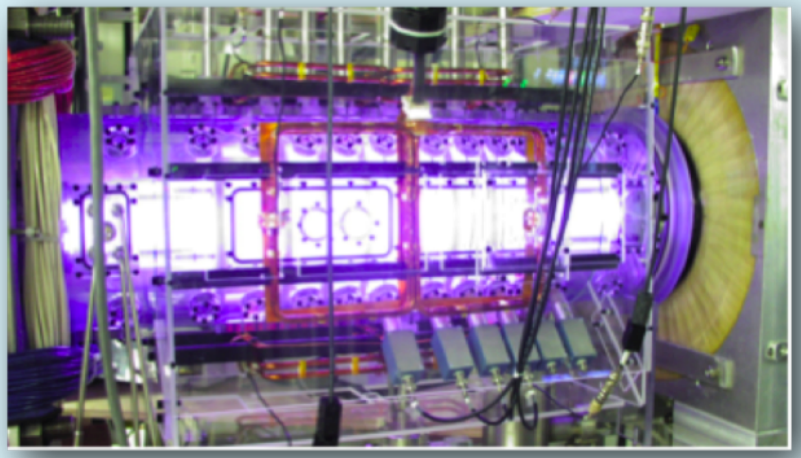
DoD Terrestrial

- The electric battlefield
- Small Naval combatants
- Forward power
- Fusion powered drones for boost phase missile defense

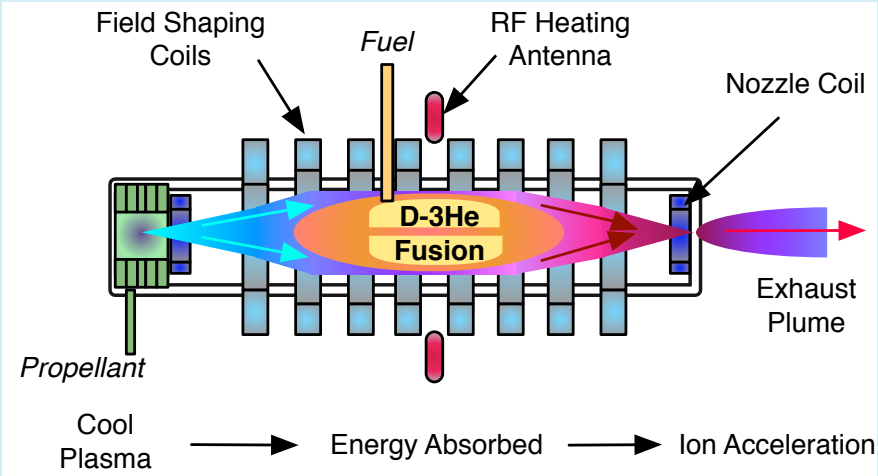


PFRC Technology: *Simple, Small, Clean*

- FRC: Field-Reversed Configuration
- Enabled by new magnetic plasma heating method
  - Steady-state operation
- ***Simple*** linear array of magnetic coils
- ***Small*** size permits ***clean*** operation (ultra low radioactivity)
- Easily direct flow for rocket engine mode



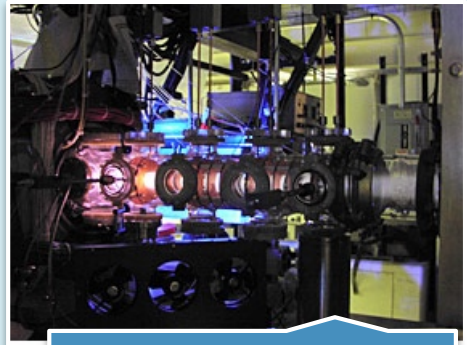
PFRC-2 in operation at PPPL



Schematic of Rocket Configuration

PPPL Princeton SATELLITE SYSTEMS

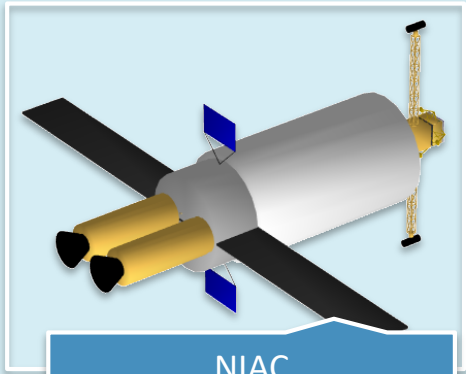
PFRC Programmatic Support to Date



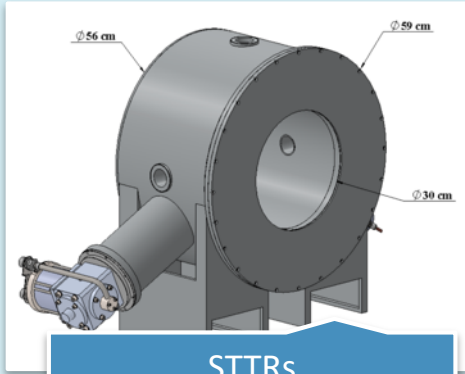
MNX
DOE 1998-2015

PFRC-1
DOE FES 2002-2009

PFRC-2
DOE FES 2010-2016



NIAC
NASA 2016-2019



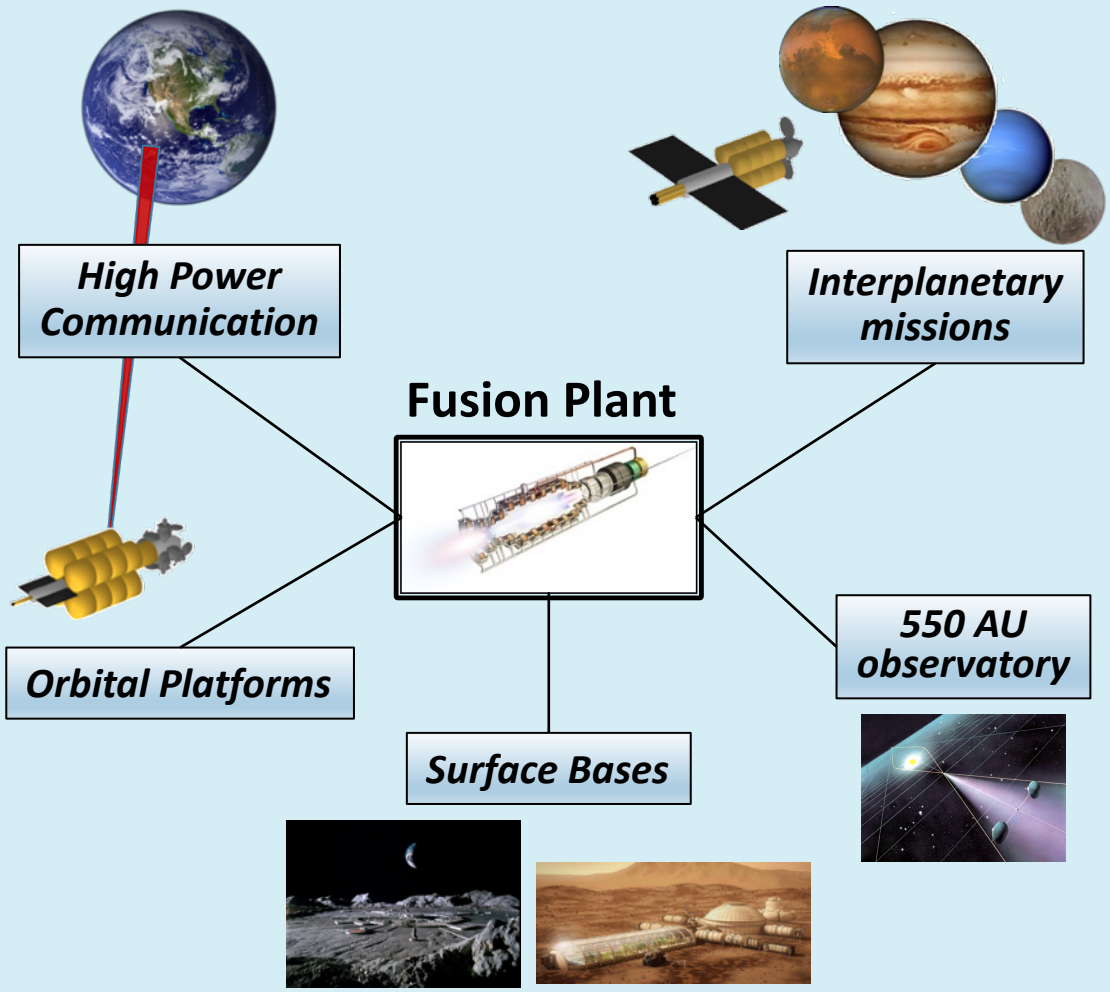
STTRs
NASA 2017-2020

ARPA-E OPEN
2019-2020

NASA Has an Interest in Small Fusion

NASA Power & Propulsion Needs

- Deep Space Gateway in cislunar space
- Manned surface bases on moon, Mars
- Orbital platforms
- Outer planet and moon missions
  - Landers and submarines to explore geology and search for life
- Near interstellar telescopes, solar gravitational lens
- Interstellar asteroid intercept
- Communications

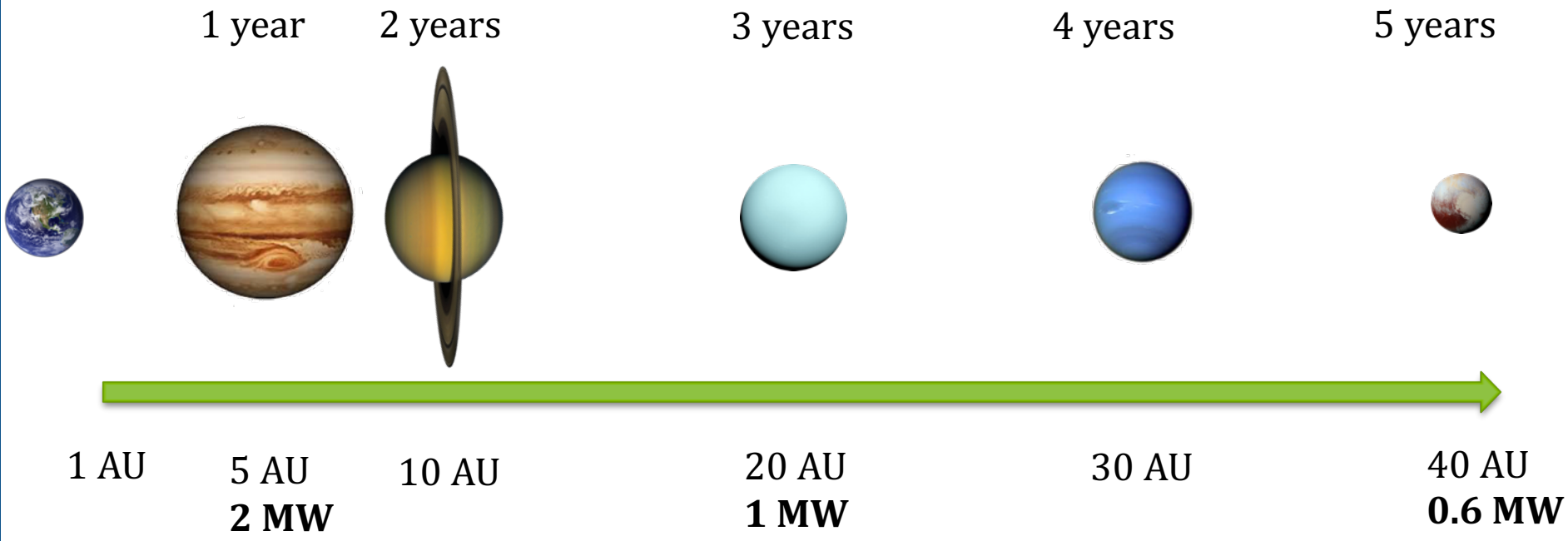


^{3}He mining & transport

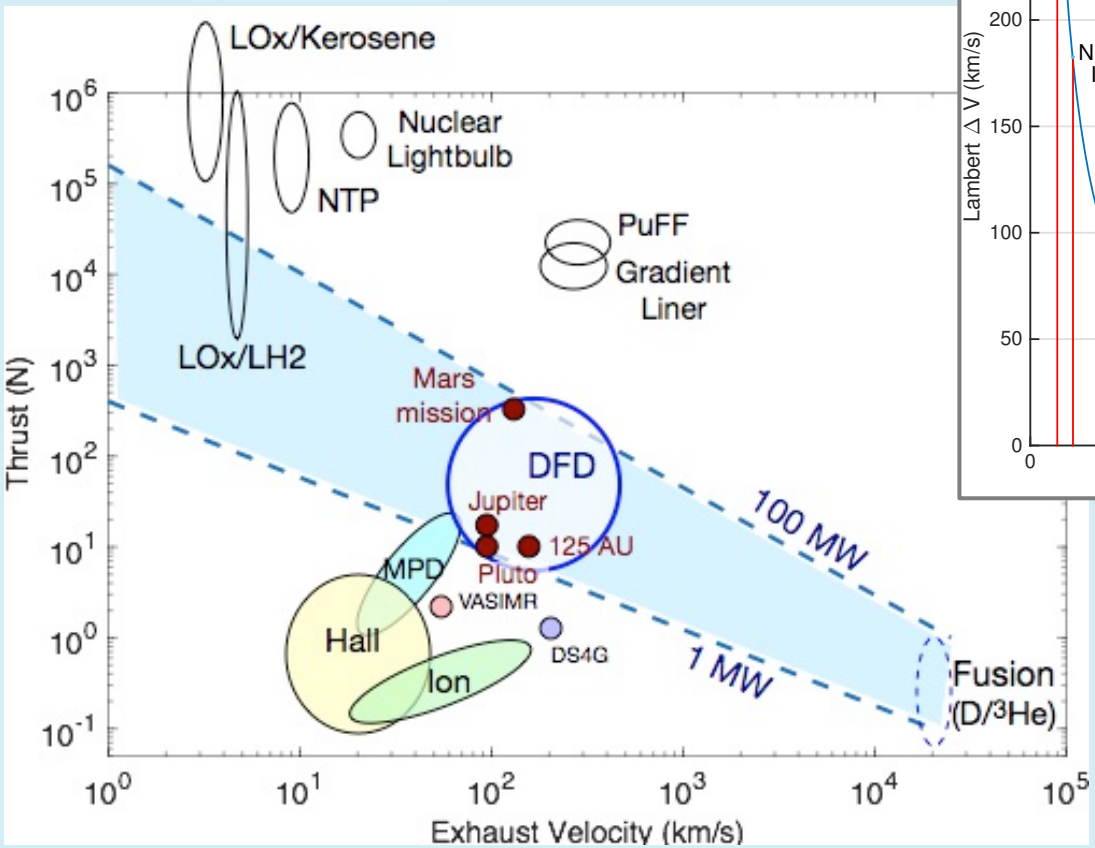
PPPL PrincetonSATELLITE SYSTEMS

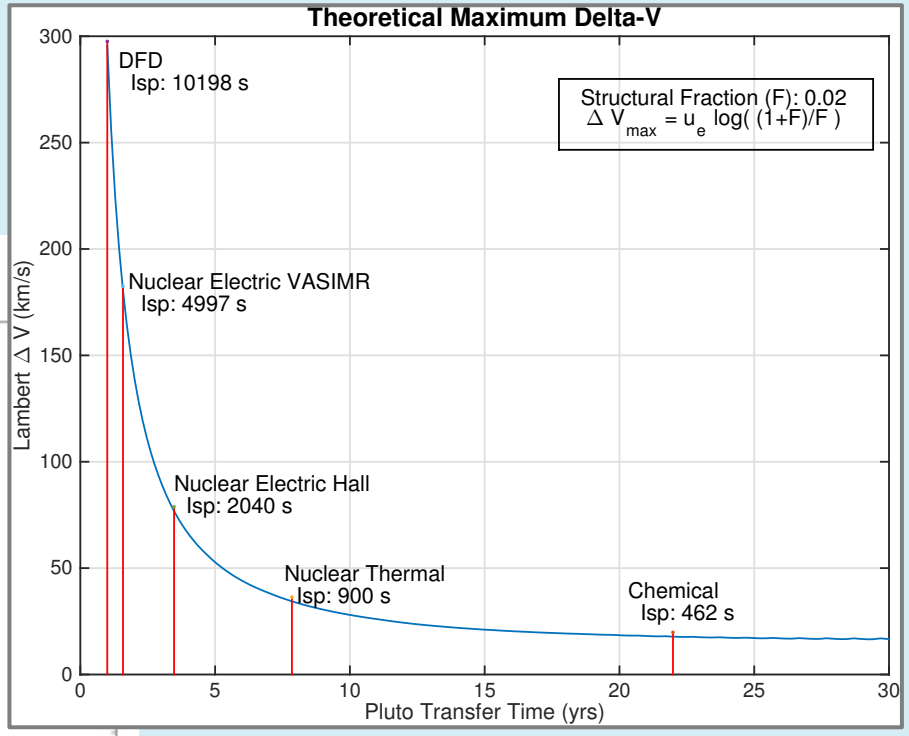
Why **Fusion Propulsion**: Deep Space Rapid Transit

What can you do with a **1-2 MW fusion engine** and a **10,000 kg** mission?



Advanced Propulsion Big Picture



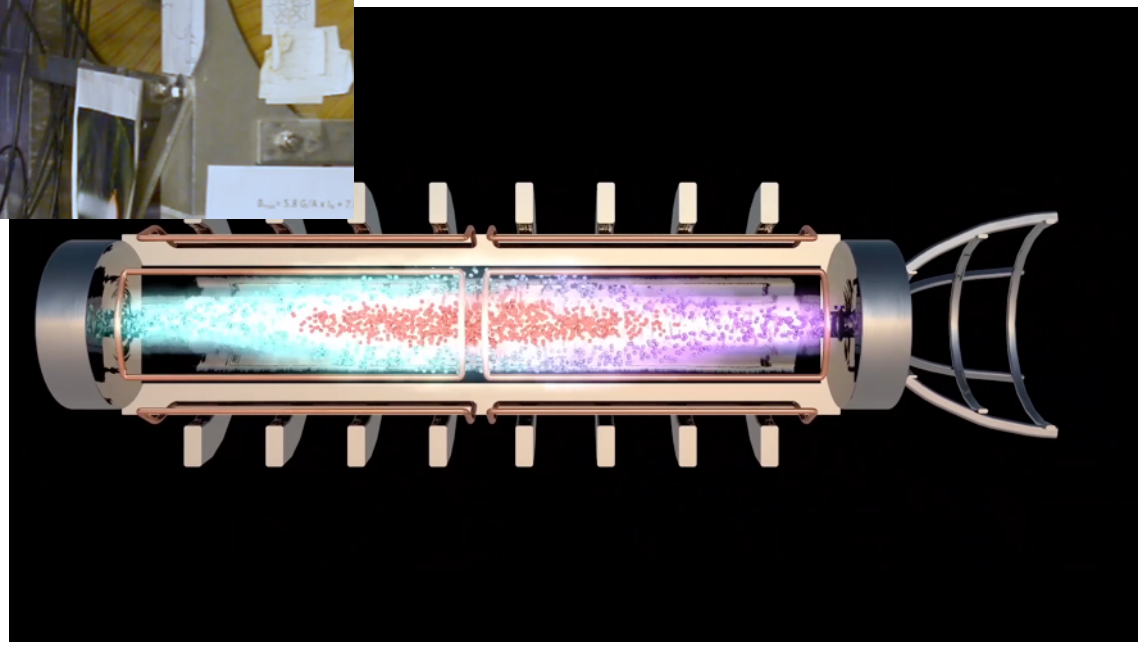


Achievable delta-V is fundamentally limited by the structural fraction and exhaust velocity…

DFD Technical & Team Videos on Website

https://youtu.be/vS4o7W3UP4M

https://youtu.be/hggqvB5I95I



DFD: Propulsion and Power in One *Compact* Device

The engine uses

RF heating

to create a

CLOSED field lines,

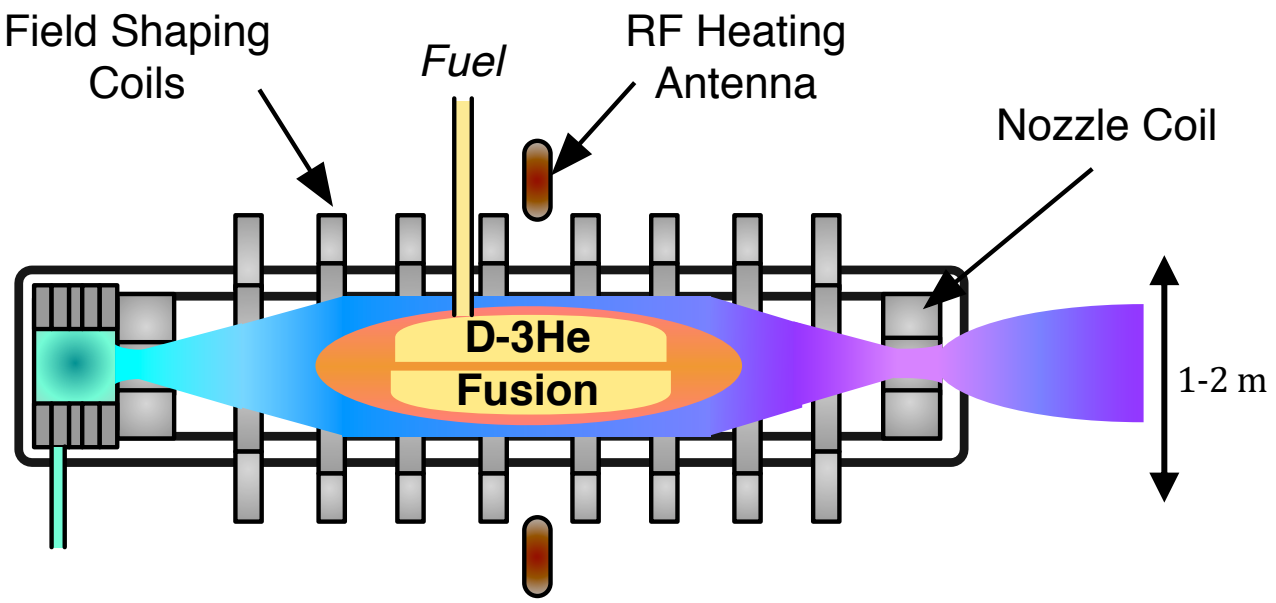
Field-Reversed Configuration (FRC)

inside a

magnetic mirror,

producing

power AND thrust



Propulsion and Power in One Device

The fusing plasma acts as the

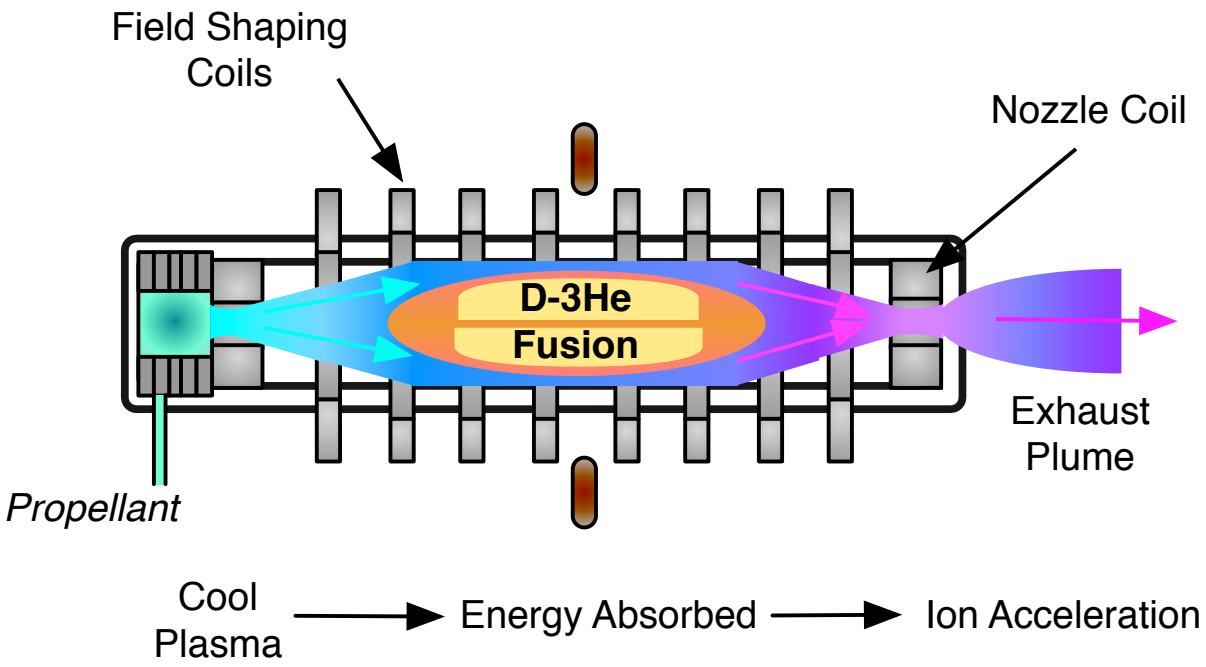
heating source

for cool propellant flowing outside the confinement region. This process of

thrust augmentation

gives us substantial thrust with high exhaust velocity!

Thrust: ~5-10 N/MW_f
Impulse: ~10,000-20,000 s

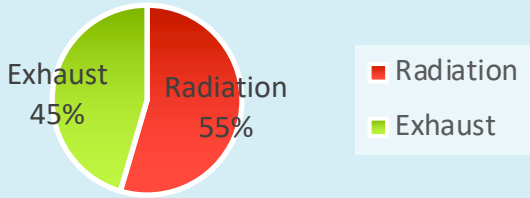


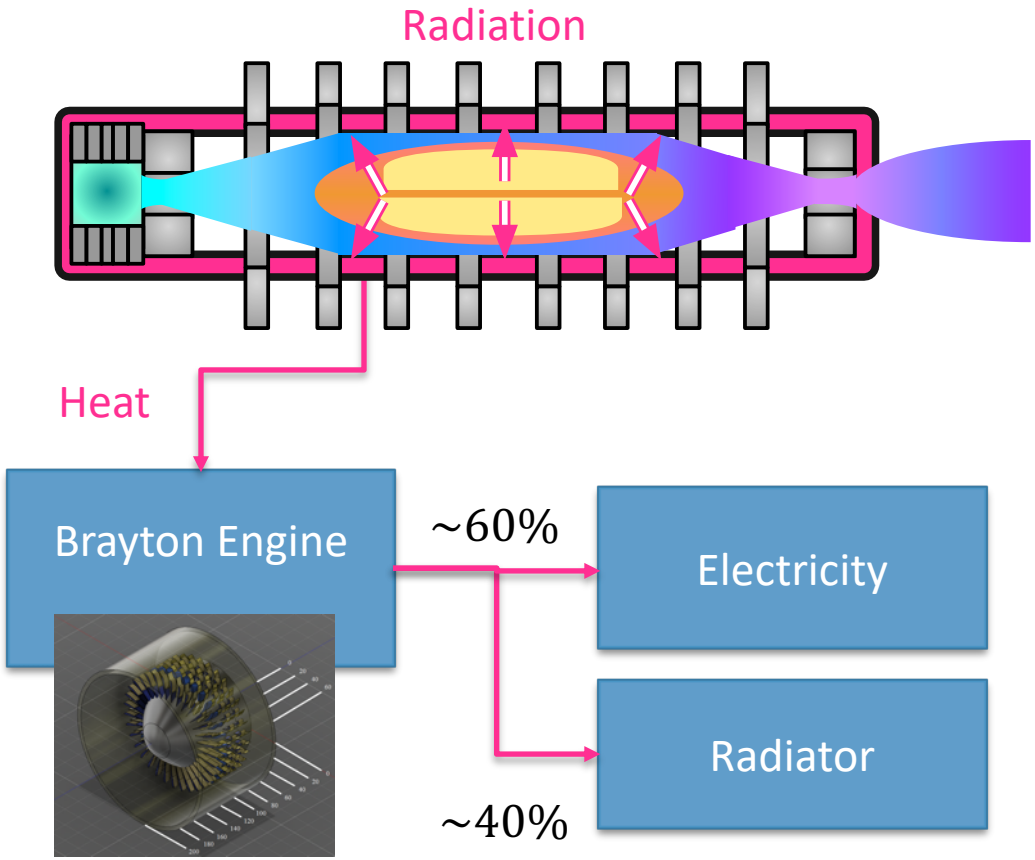
Power and Propulsion in One Device

Producing power:

- Fusion deposits **heat** in the walls (x-rays and microwaves)
- Brayton cycle engine converts heat to **electricity**
- Excess heat rejected to space

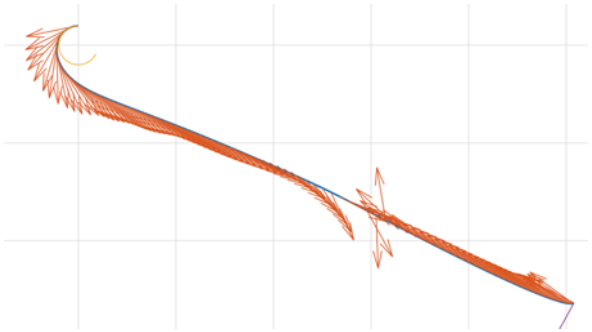
Fraction of fusion power:

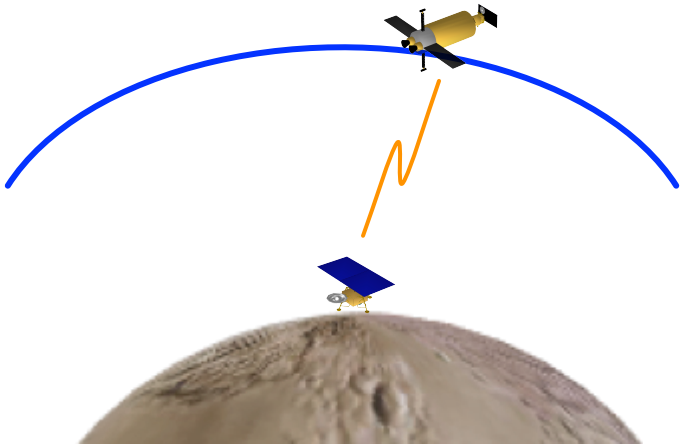




NIAC: Pluto Explorer Mission with DFD

Single launch from Earth, **fly directly to Pluto** with constant thrust

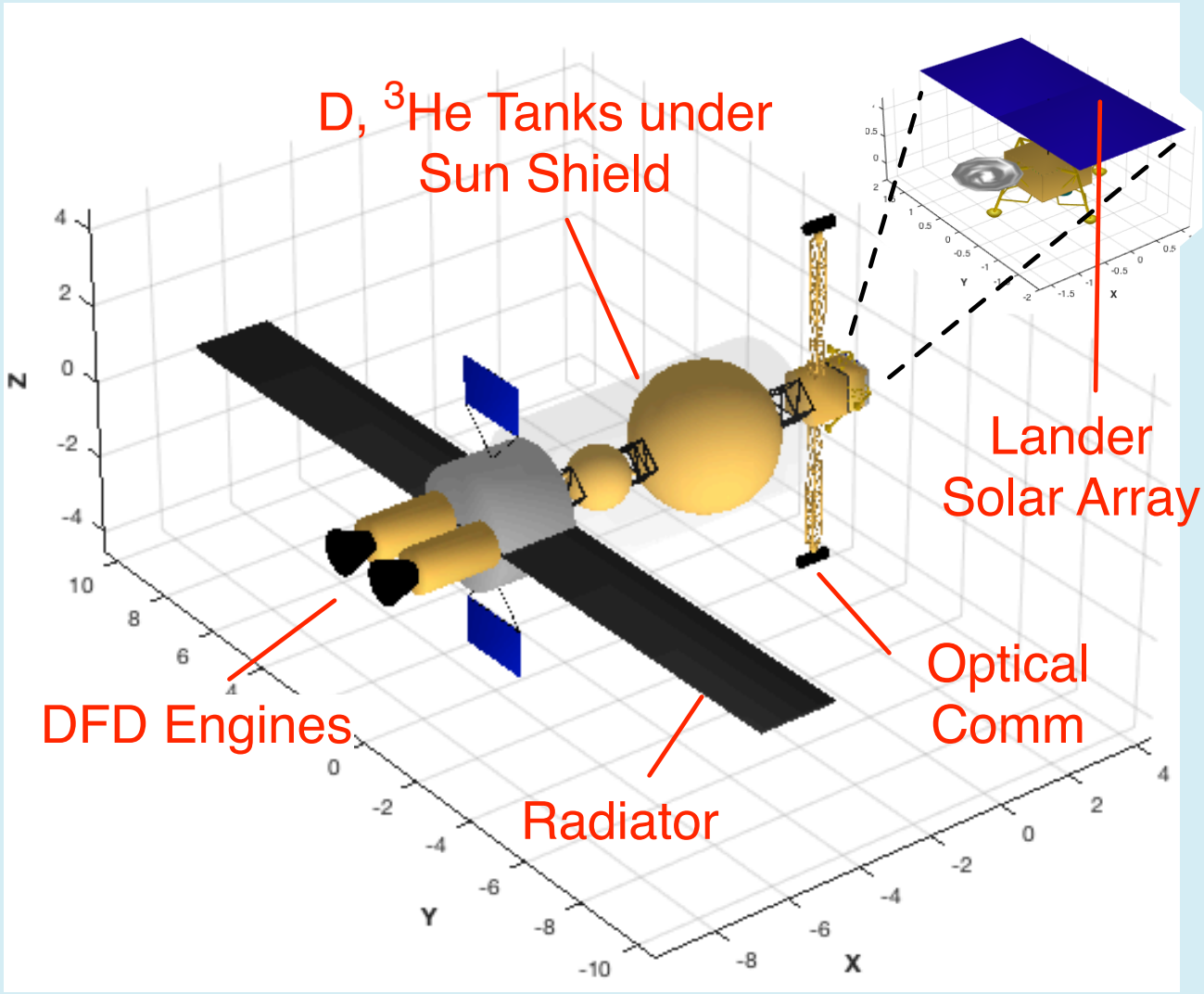




Engine	1100 kg
Radiator Area	120 m^2
Radiators	250 kg
Fuel (D_2)	7250 kg
Helium-3	0.5 kg
Liquid D_2 tank	2.6 m radius
Gas ^3He tank	0.95 m radius
Fuel Tanks	400 kg
Lander	200 kg
Structure	300 kg
Orbiter payload	500 kg
Launch Mass	**10000 kg**

Put a 1000 kg spacecraft in orbit around Pluto,
beam power to a lander using optical transmission,
return high-definition video –
and get there in less than **5 years**!

NIAC Pluto Explorer Vehicle Design



STOP RIGHT THERE.

How is a **fusion drive** suddenly achievable?

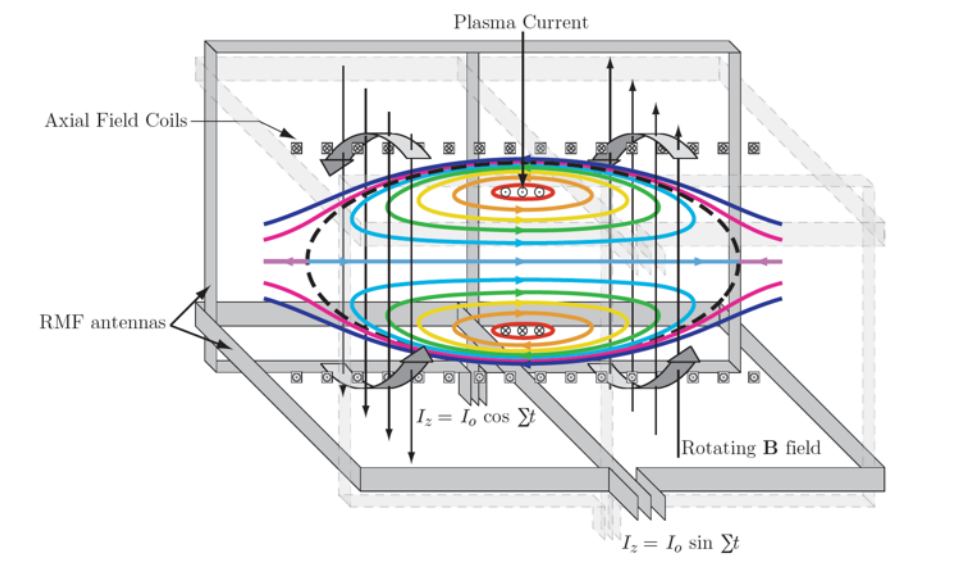
DFD is DIFFERENT from other fusion reactor concepts

1. **Unique heating method**
2. **SIMPLE configuration**
3. **SMALL size**
4. **CLEAN operation – low radiation**

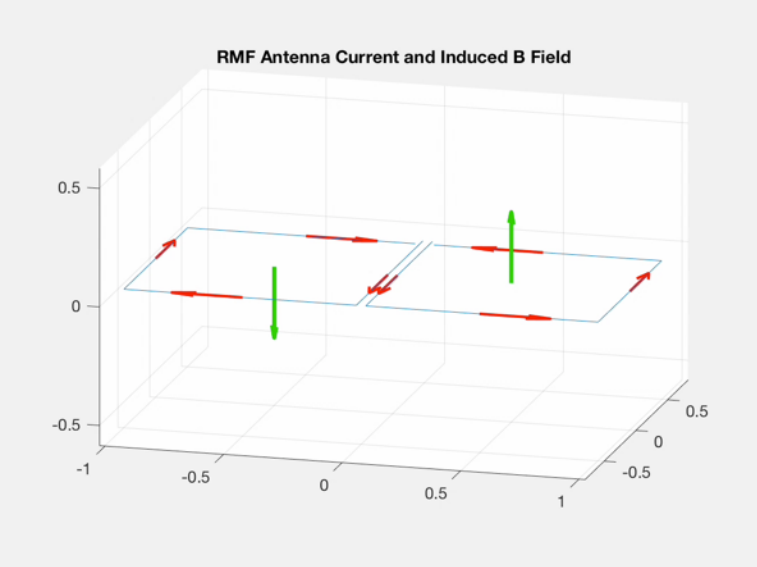
→ FRC has 10x better confinement than tokamak
→ FRC has 20x higher β
→ FRC can contain 5x higher density

These features make it uniquely suited for use in space!

Unique Heating: RMF Current Drive



- Antenna currents creating rotating magnetic & electric field
- Current is ***driven***
- Very efficient drive at magnet null
- **Closed field lines**



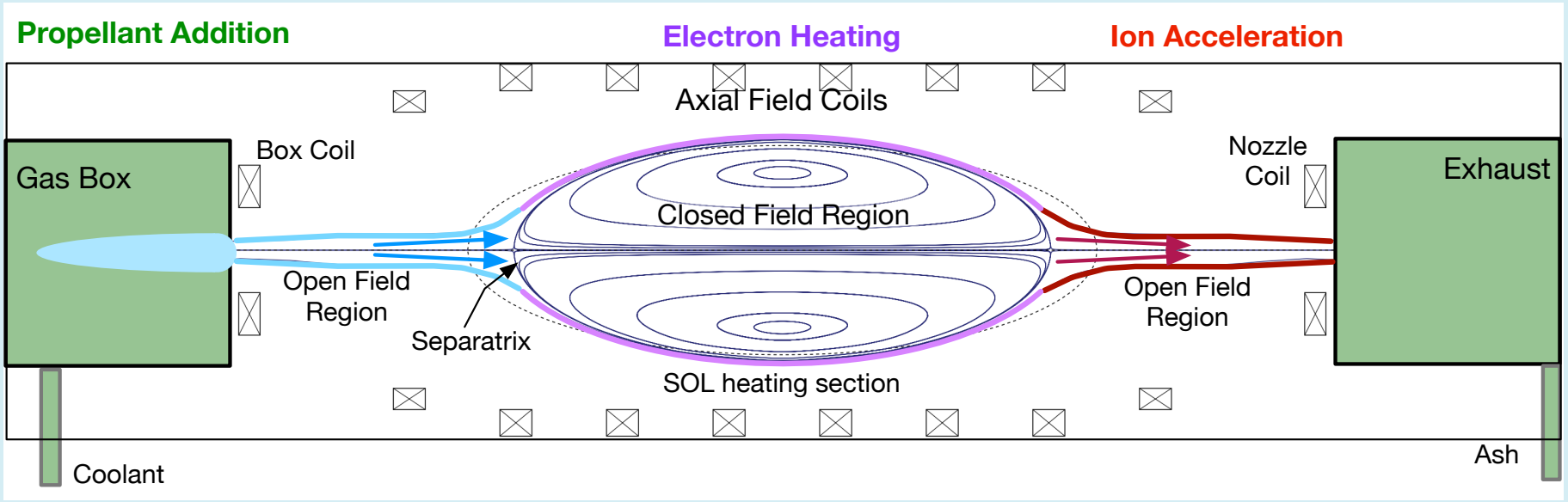
(still from an animation)

"odd-parity" -- fields are in opposite directions on either side of machine midplane

"even-parity" – single antenna loop; open field lines

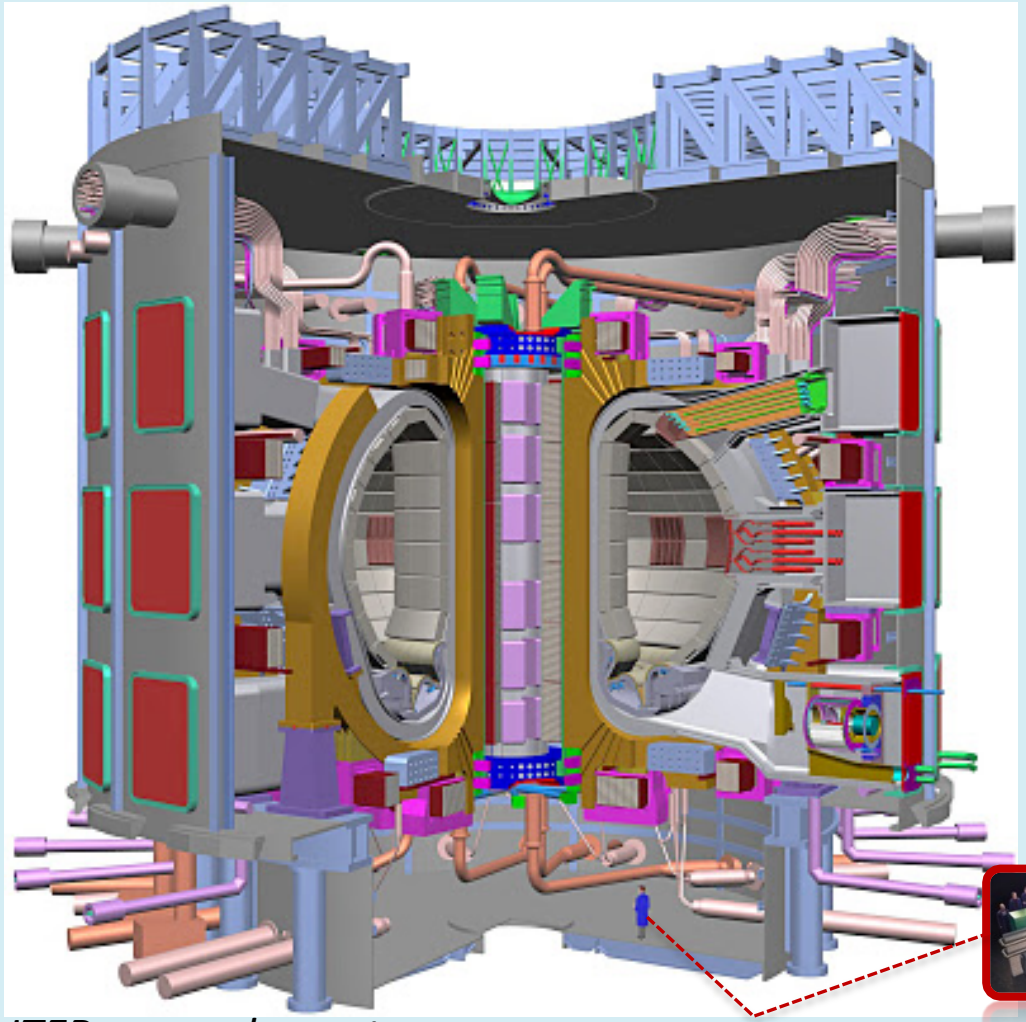
PPPL Princeton SATELLITE SYSTEMS

Simple: Linear Array of Coils



The linear configuration means the reactor could be assembled in segments and simply pulled apart as needed.

Small: DFD is REALLY small



ITER research reactor

Person for scale

Typical tokamak reactor:

- 1000-4000 MW
- 60 m tall
- Development in 30-50 years

PFRC reactor:

- 1-10 MW
- 2 m diameter
- Development in 5-10 years
- Small enough to fit on a single launch vehicle

PPPL Princeton SATELLITE SYSTEMS

Clean: D-^{3}He can burn Aneutronic fuels

Main Fusion Reaction

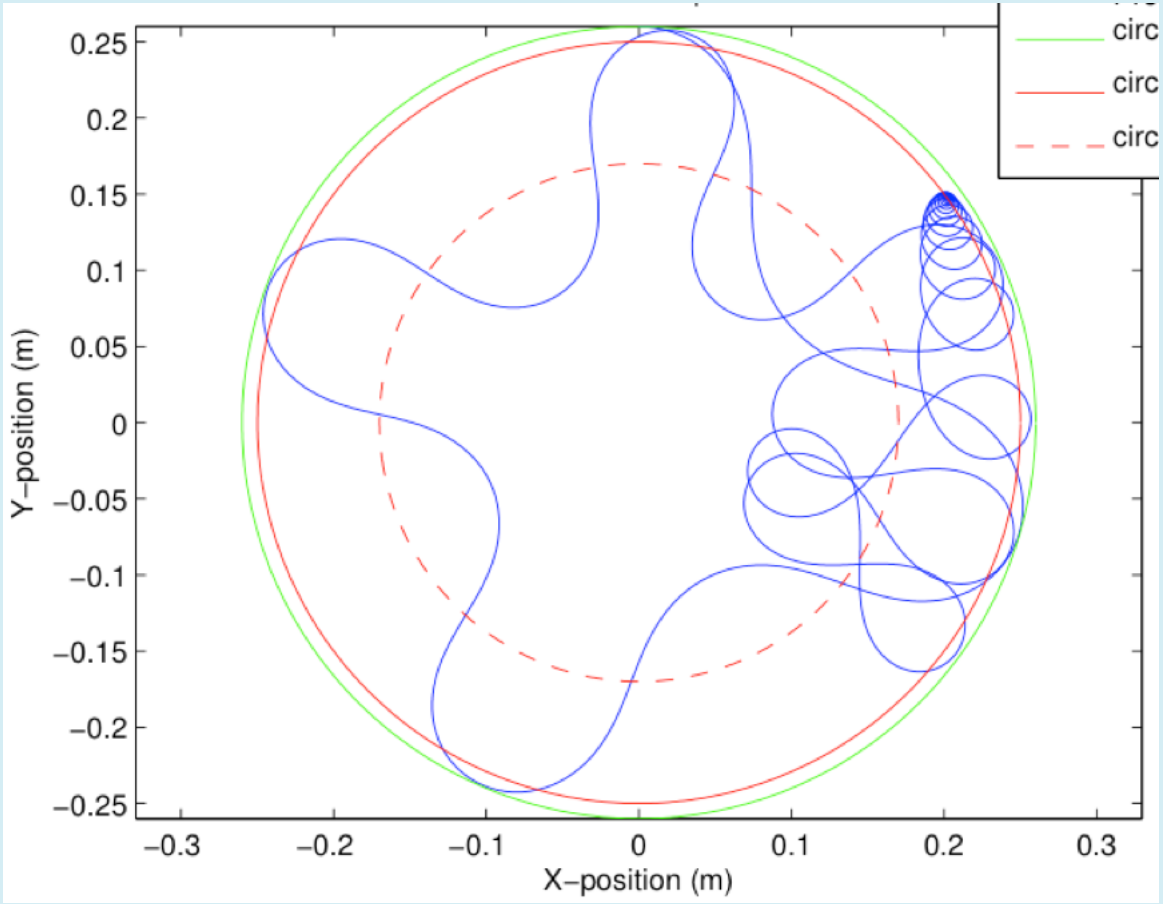
	Power
- D + ^{3}He → ^{4}He (3.6 MeV) + p (14.7 MeV)	98.4%

Side reactions

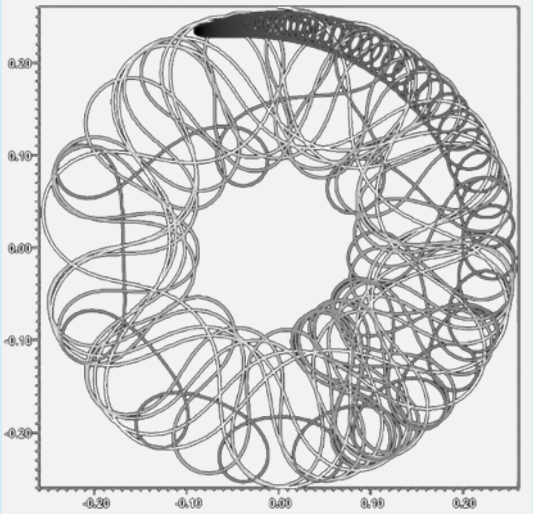
- D + D → T (1.01 MeV) + p (3.02 MeV)	0.88%
- D + D → ^{3}He (0.82 MeV) + n (2.45 MeV)	0.72%
~~- D + T → ^{4}He (3.5 MeV) + n (14.1 MeV)~~	<0.05%

T → cooled and exhausted before it can fuse
^{3}He → exhausted
^{4}He → exhausted
p → exhausted
n → deposit energy in walls as heat

Tritium Ash Removal

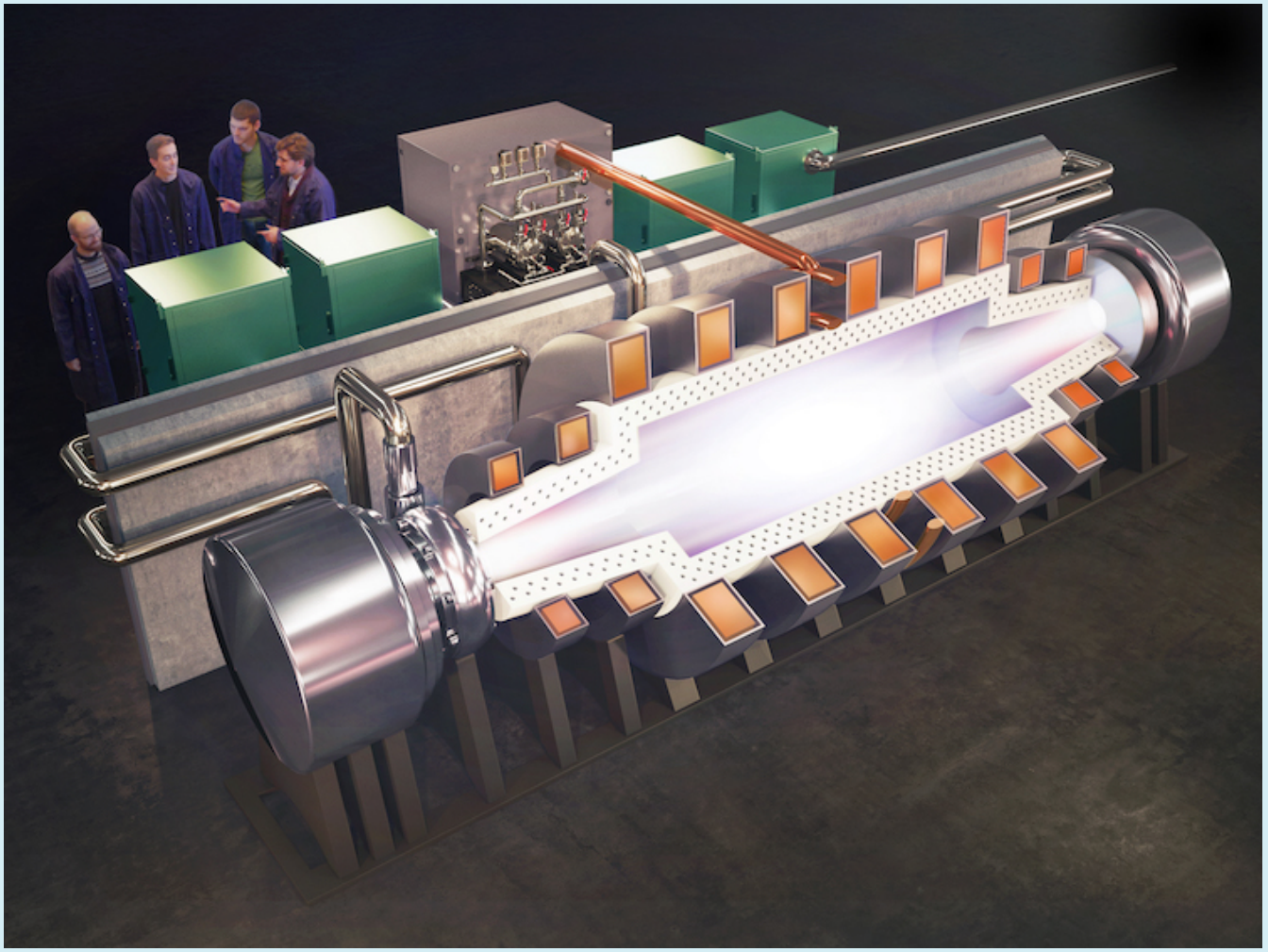


In the above graph, just a few orbits of each type are shown. An animation is included in our technical video.

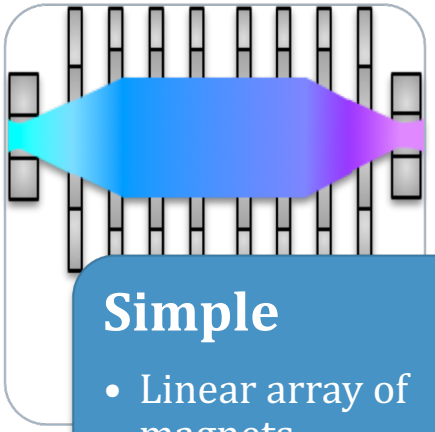


In actuality, hundreds of orbits occur before the tritium is captured on a SOL field line – time < 20 ms!

CLEAN: Ultra low radiation

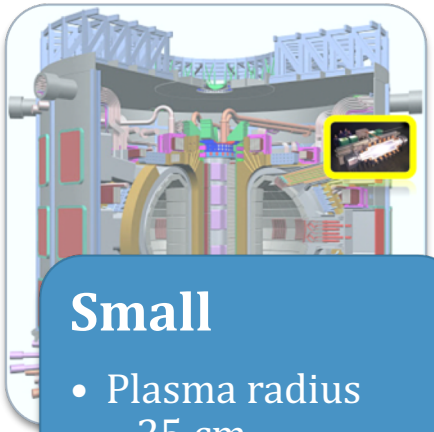


DFD is **DIFFERENT** than other fusion concepts



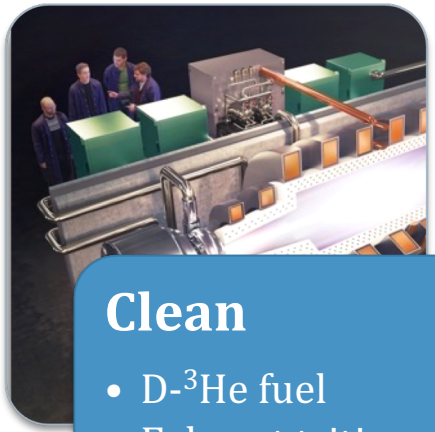
Simple

- Linear array of magnets
- Easily directed plume



Small

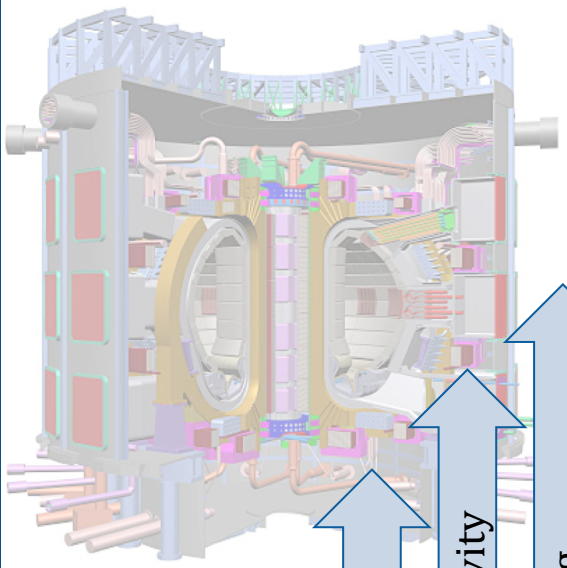
- Plasma radius ~25 cm
- Engine is 1-2 m diameter



Clean

- D-^{3}He fuel
- Exhaust tritium before it can fuse
- <1% power in neutrons

Why now?
Its ***Faster*** and ***Cheaper*** to Develop a ***Small*** Machine



Tokamaks
> 200 MW

Size

Radioactivity

T Breeding

Complexity

Time: > 20 years

Cost: >$10B

Small FRC
< 10 MW

Size

Radioactivity

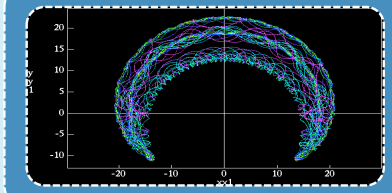
Available Fuel

Complexity

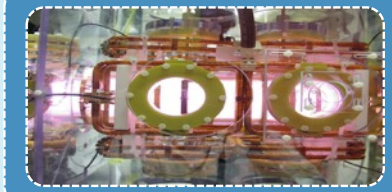
Time: < 5 years

Cost: <$100M

Summary of Key Physics Points

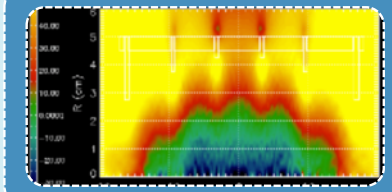


Hamiltonian code ("RMF") showed current drive and rapid ion and electron heating.



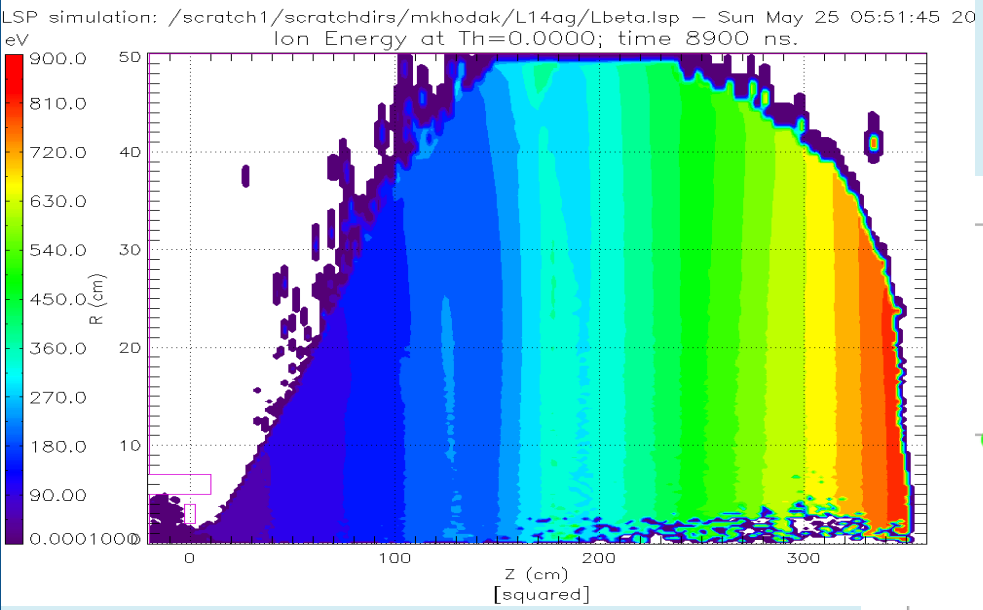
PFRC-1 demonstrated rapid electron heating, stability 10^3 x better than predicted by MHD, and, indirectly, FRC formation

PFRC-2 thus far has demonstrated 100x improved particle confinement and stability 10^5x better than predicted by MHD



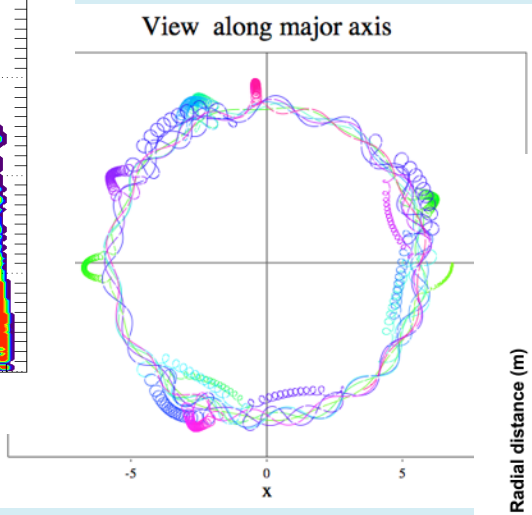
PIC model demonstrated current drive, field reversal by RMF_o, and excellent agreement with full x-ray EEDF

Computational Tools Applied



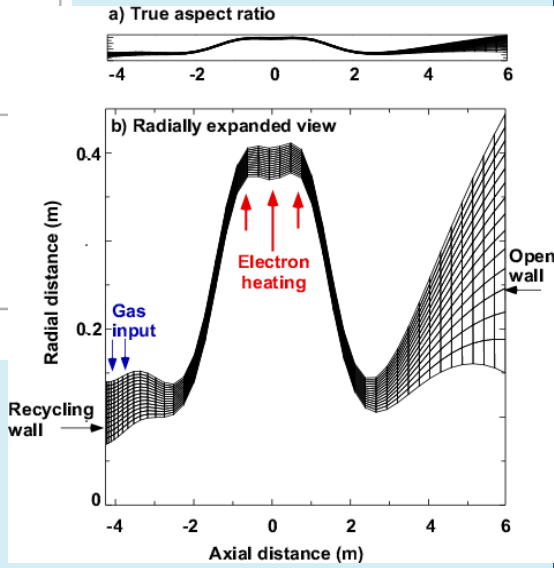
Expanding plume; leading edge of the D+ plume is getting to 900 eV, Isp = 30,000 s

LSP: particle in cell; kinetic



Orbit of ion heated by RMF

RMF: single particle; Hamiltonian

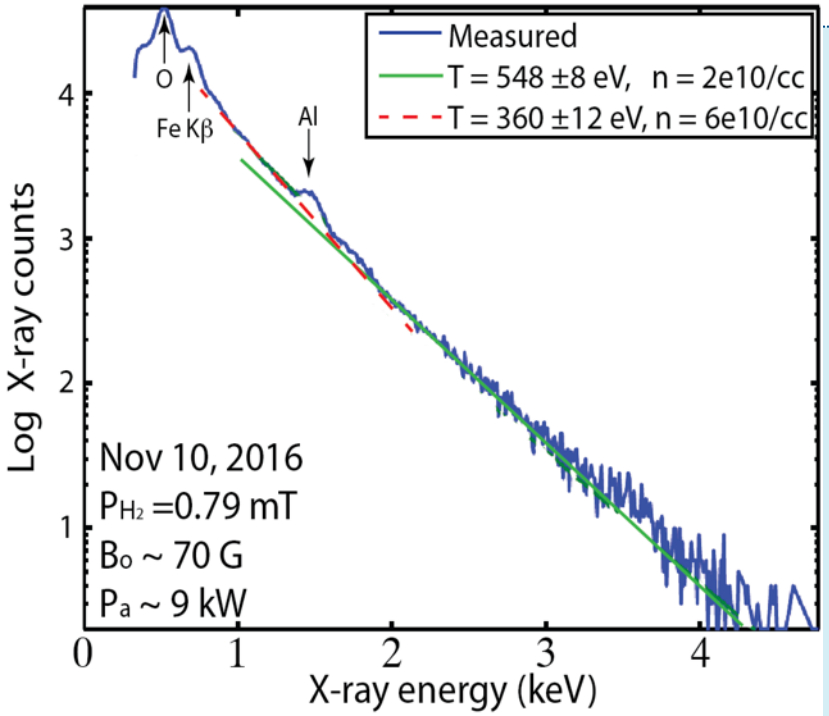


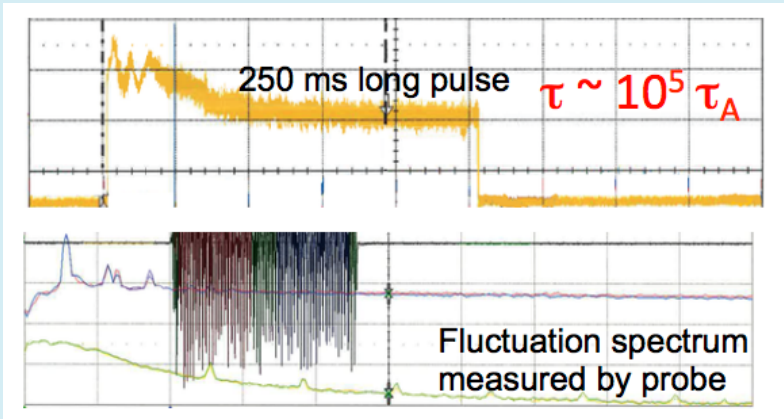
Model of plasma heating and flow in SOL

UEDGE: multi-species fluid model

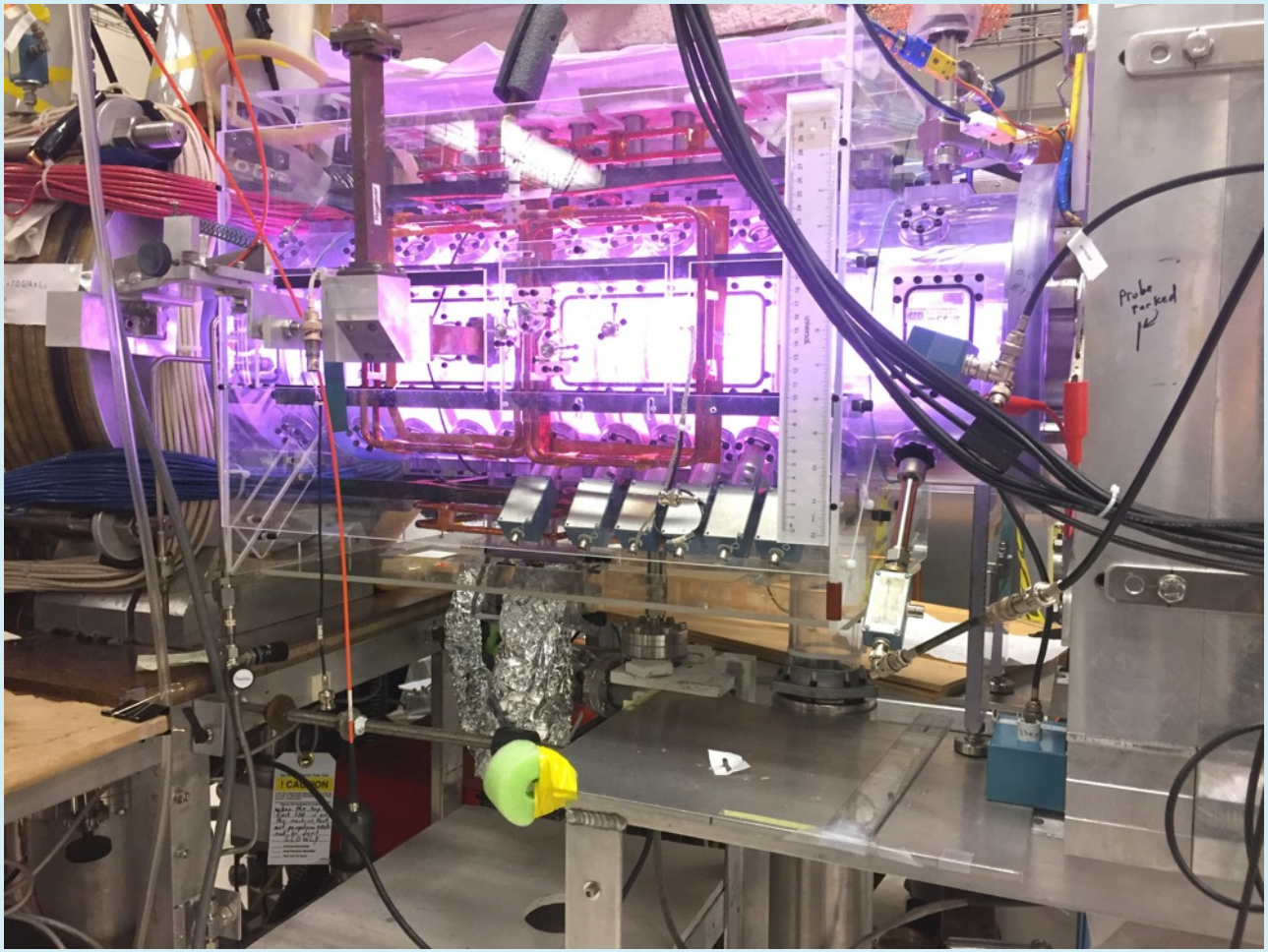
Experimental Apparatus

- Concluded PFRC-1 a, b, c in 2011; **breakthrough** achieved in FRC electron heating methods
  - Electron heating to > 200 eV
- PFRC-2 operating now
  - Goal is to demonstrate keV plasmas with pulse lengths to 0.3 s
    - Electron heating to > 500 eV
  - Operated with up to 40 kW power
  - MNX computational studies on plasma detachment via magnetic nozzle (LSP)
- Major upgrades taking place under new ARPA-E OPEN grant
  - Higher RF and magnet power
  - Lower frequency to heat ions





PFRC-2 Experiment



TWO NASA PROJECTS:

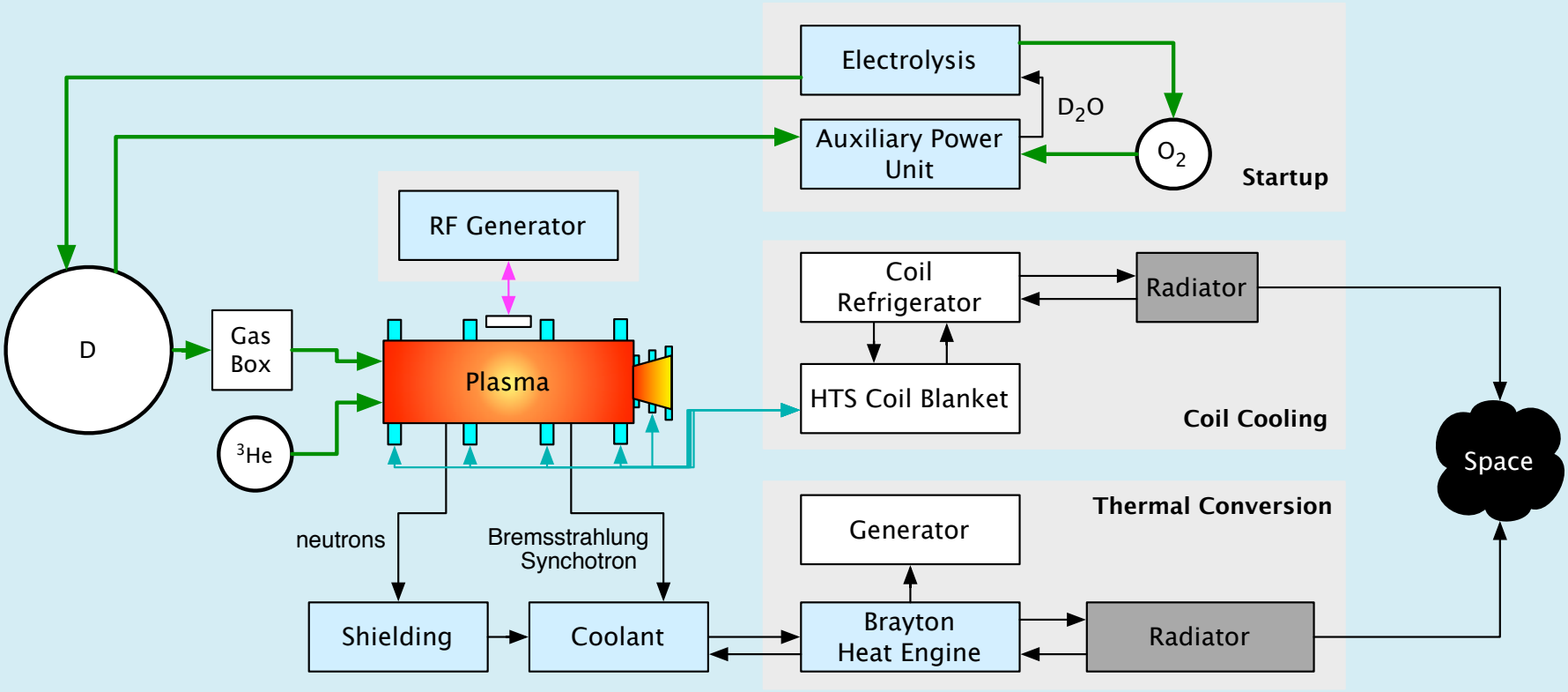
1. NASA NIAC STUDY
2. NASA PHASE II STTR

Questions to Answer

1. Can PFRC really produce (net power from) fusion?
2. Can DFD be made to operate for long durations in space?
3. Can DFD achieve the necessary specific power for the desired mission parameters?

Our NASA work is primarily addressing questions 2 and 3; continuing work at PPPL, and our new ARPA-E OPEN grant, address question 1.

NIAC: Systems Analysis of the DFD Engine



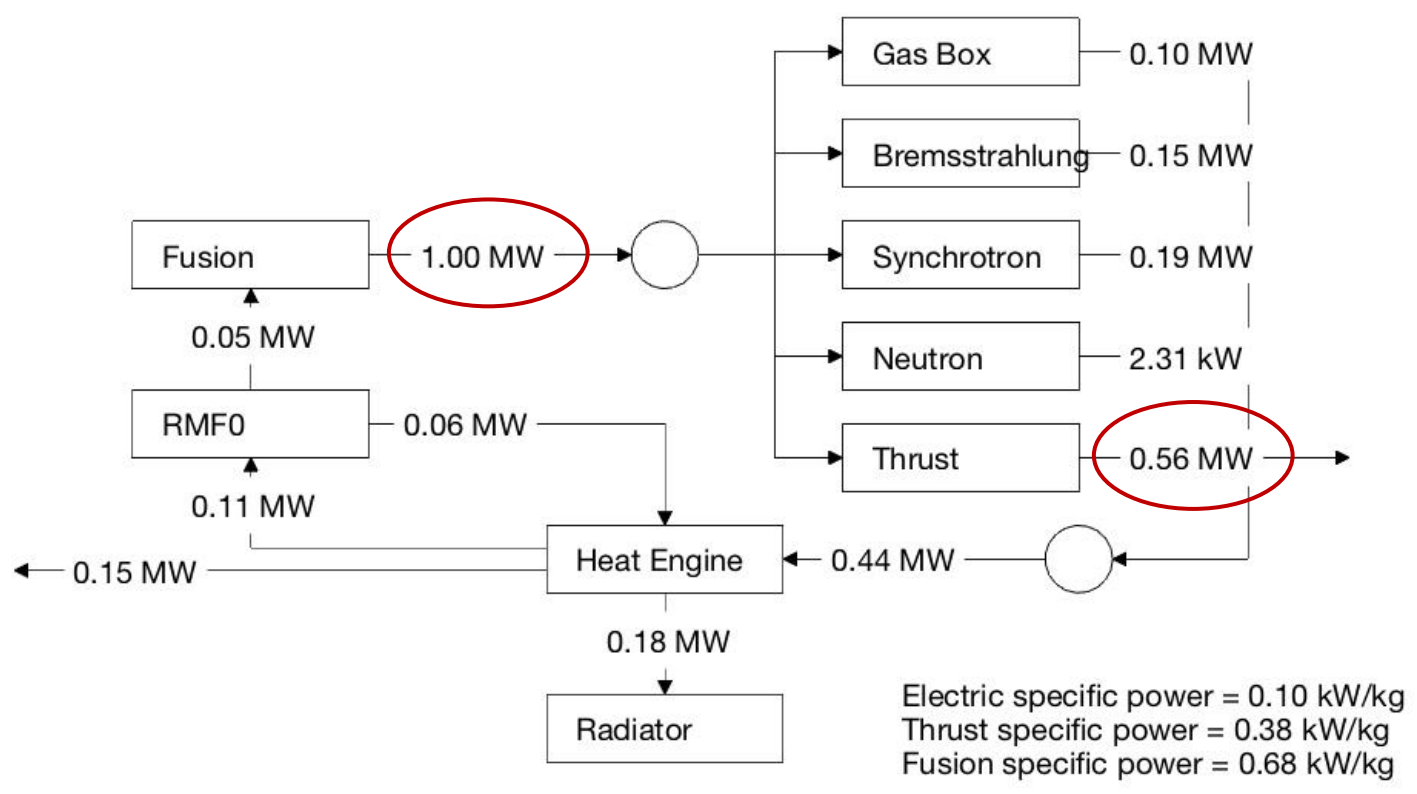
Typical Reactor Parameters

Parameter	Value
Fuel	D-3He
Fuel Ratio	1:3
r_s	0.3 m
Elongation, K	5-10
B_{axial}	5-7 T
B_{nozzle}	20 T
B_{RMF}/B_{axial}	~0.1-0.5%
β	0.85
Plasma current	10 MA

The fuel ratio sacrifices some power density for lower radiation (less D-D fusion).

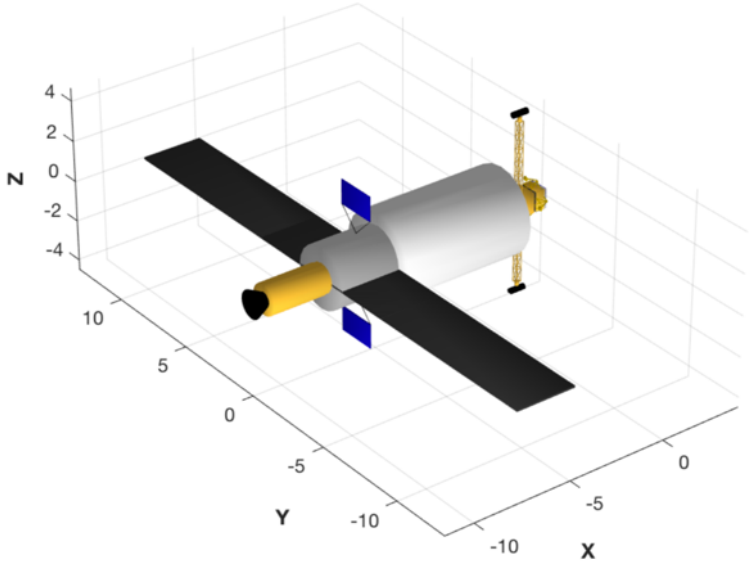
Parameter	Value
n_e	$3\text{-}5\times10^{20}/m^3$
T_e	50 keV
T_i - Deuterium	70 keV
T_i – Helium-3	70-140 keV
S*/K	2.8 (kinetic)
γ_{LH}	0.02
RF frequency	0.2 MHz
SOL temperature	20-120 eV

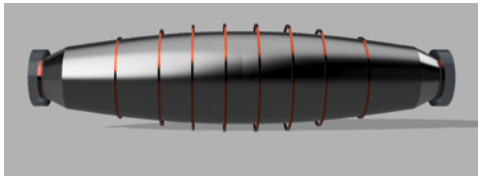
Power Flow and Specific Power – 1 MW

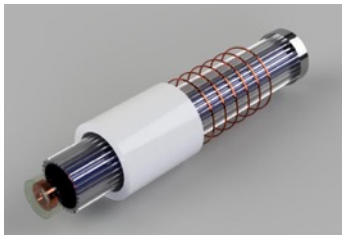


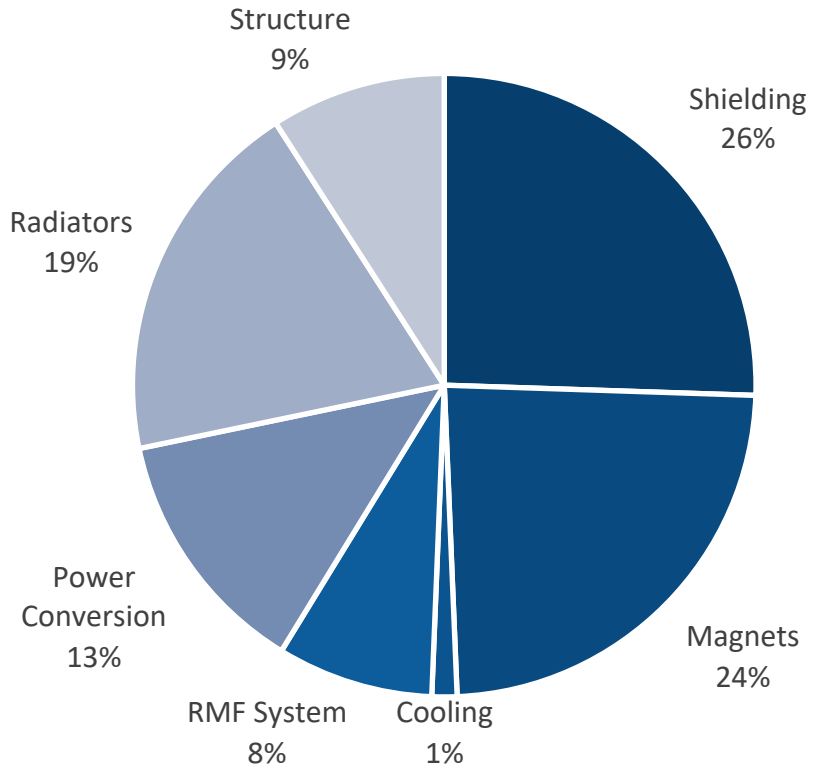
- RMF power is ~10% of the fusion power
- Specific power is higher for larger engines, since the mirror magnets remain the same
- Range, 0.5 – 1.5 kW/kg, based on assumptions for shielding and other subsystems

Engine and Spacecraft Design





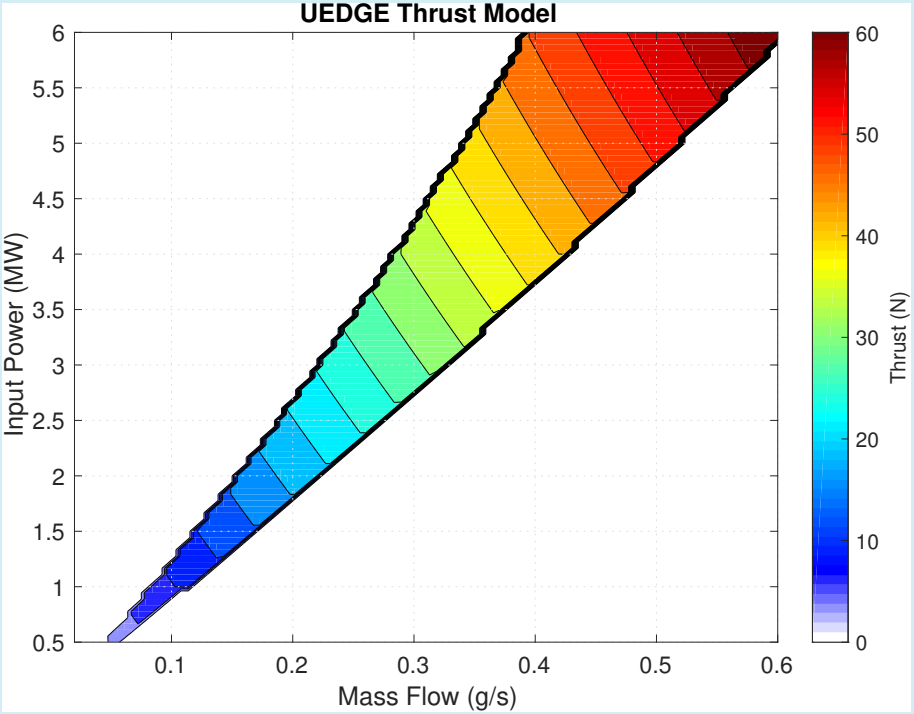


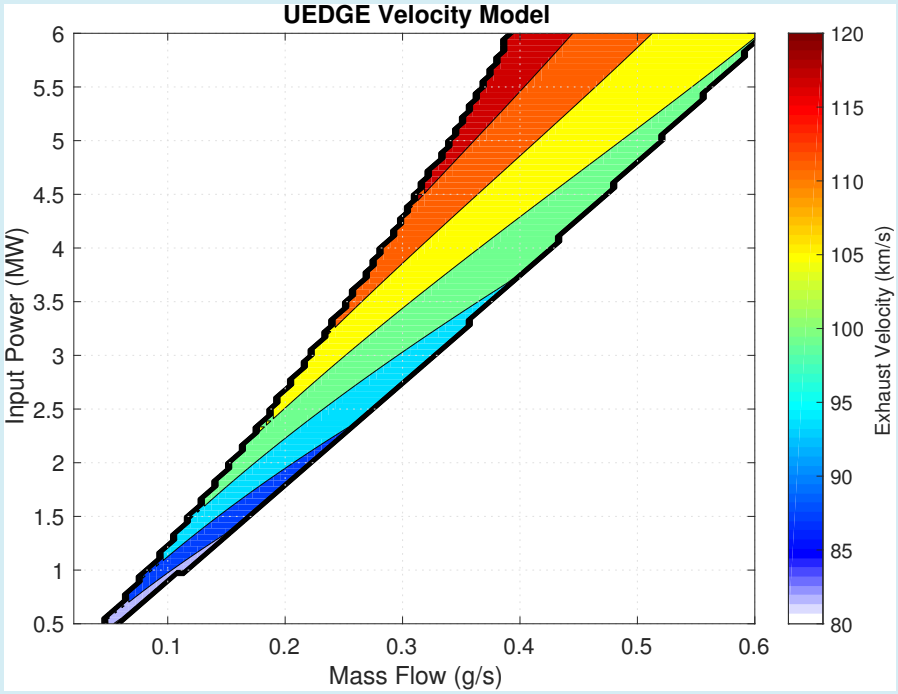


Example Mass Breakdown

Thrust and Velocity Model

Results indicate a feasible range of flow rates for the SOL to absorb the energy from the fusion products.





This gives us a numerical model to trade thrust and specific impulse.

Magnet Design Tools

New, self-consistent

Grad-Shafranov

magnetic flux solutions with plasma

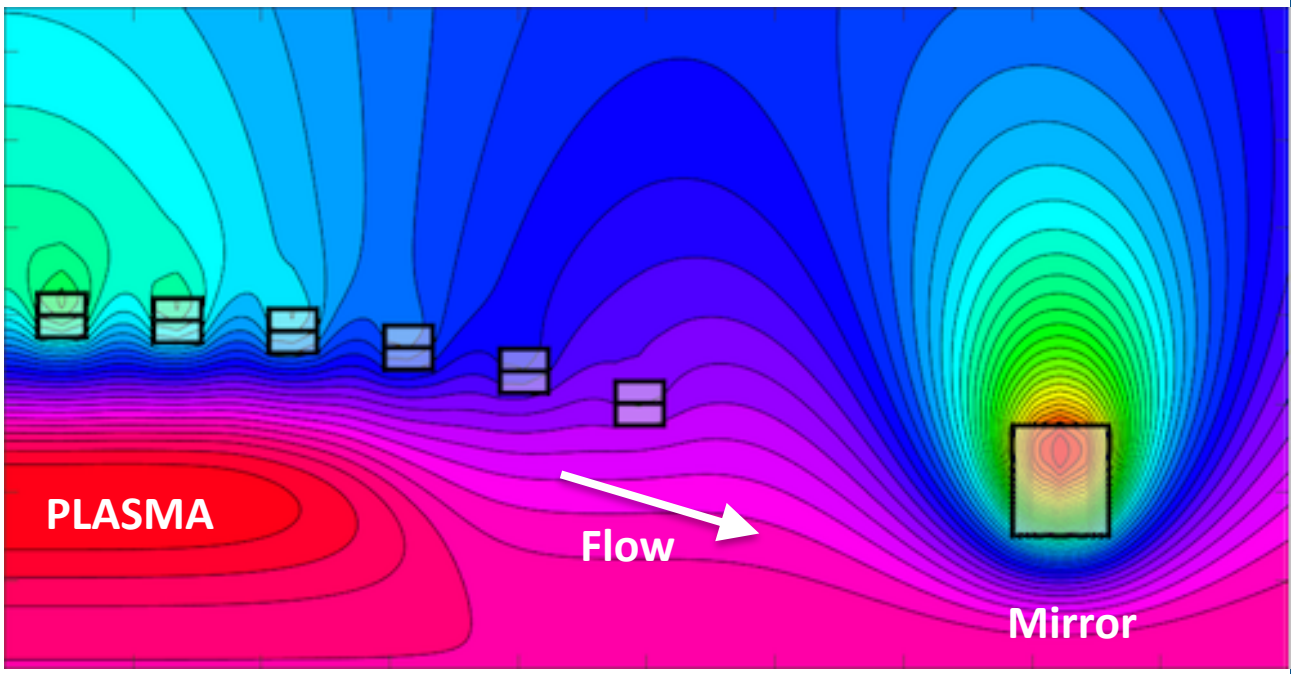
Individual magnet currents estimated

Latest design:

LTS axial magnets

AND

HTS mirror magnets



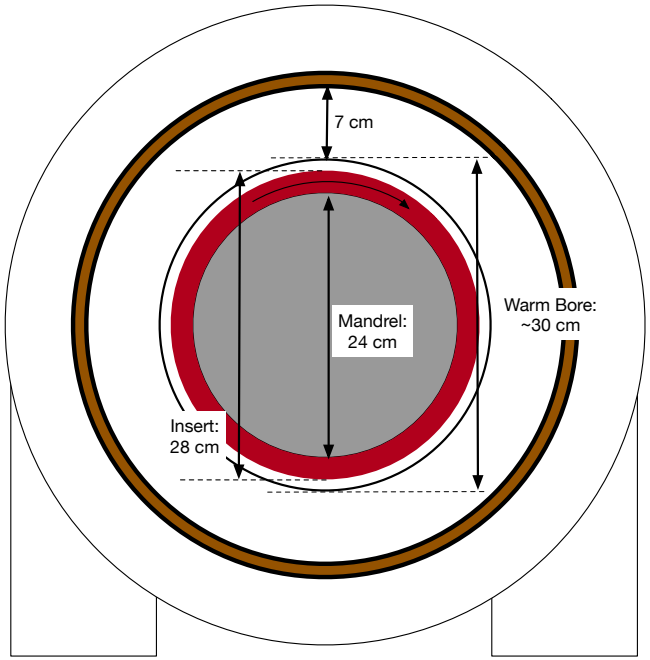
2-3 T axial magnets
5-7 T central field

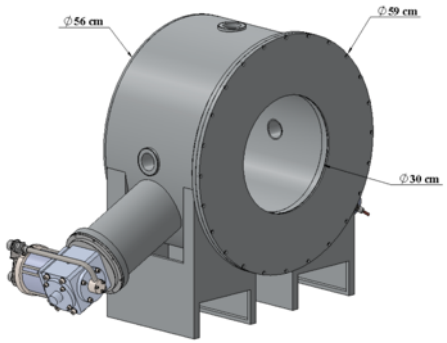
20-30 T mirror

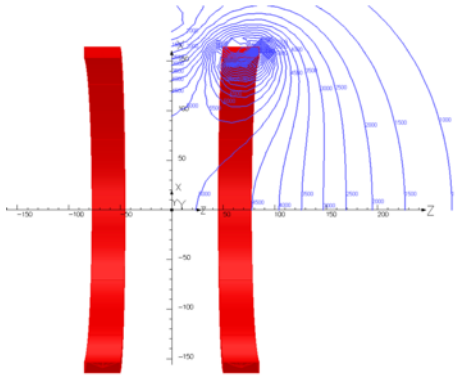
Grad-Shafranov: equilibrium equation in ideal magnetohydrodynamics (MHD) for a two dimensional plasma

New Work: Magnet STTR Phase II

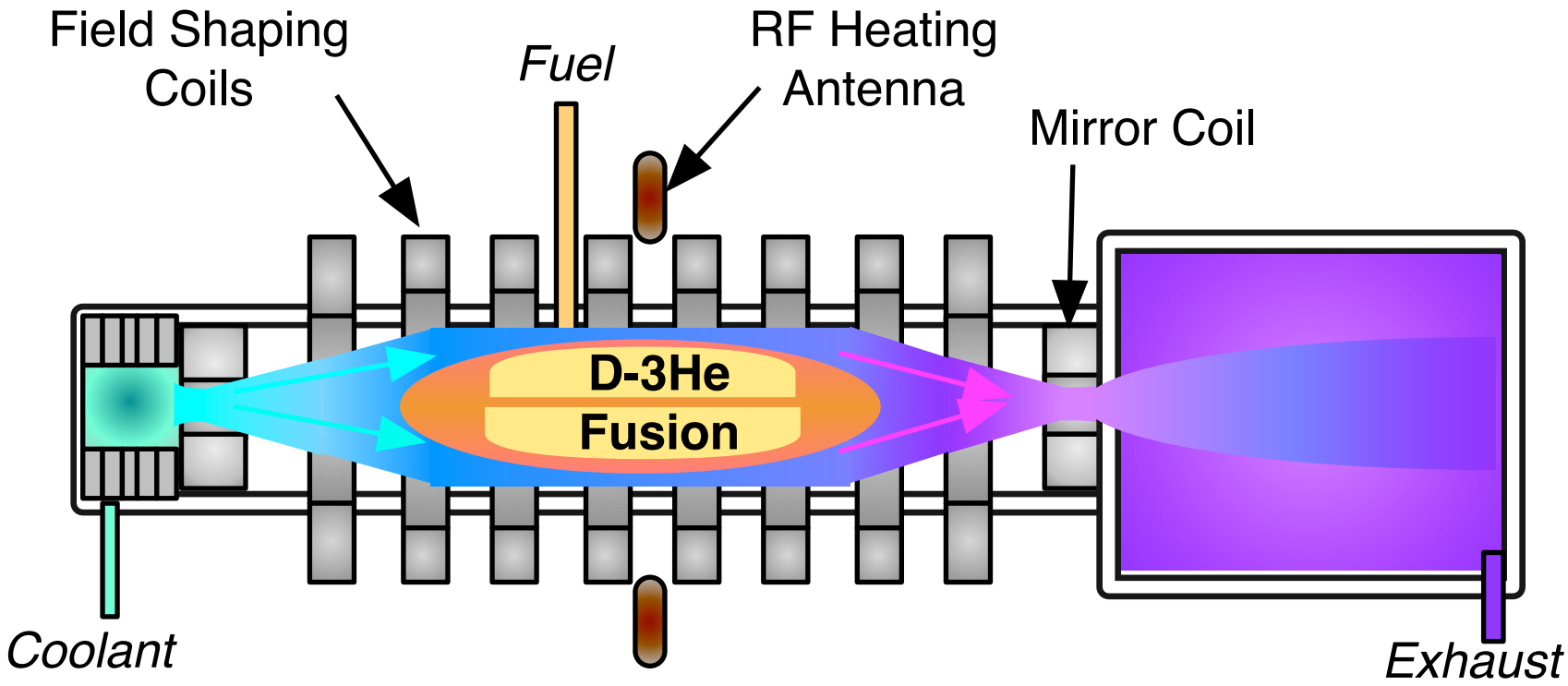
- T2.01 Advanced Nuclear Propulsion
- New Phase II STTR
- Create an LTS magnet testbed
- Use pulsed inner copper coil to simulate FRC plasma formation
- Test impact on magnets of plasma formation in close proximity
- Design HTS magnets in detail







Closed-Loop Power Plant Design



Cool Plasma → Energy Absorbed → Heat and Ash Extraction

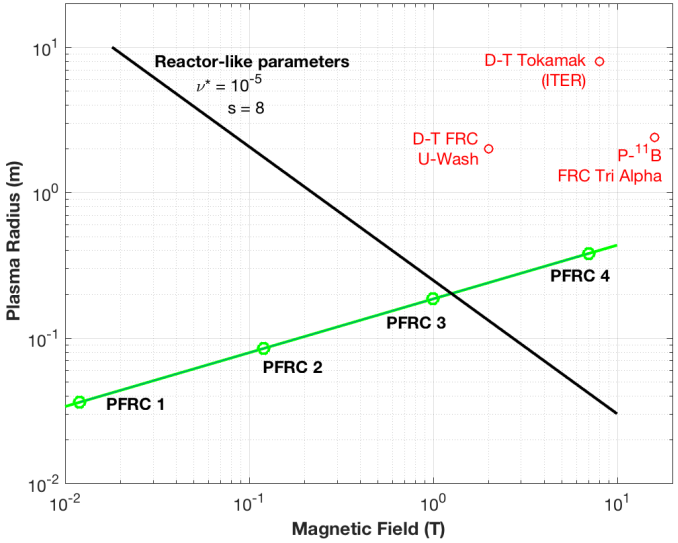
NEXT STEPS AND ROADMAP TO FLIGHT

Path to Fusion in the PFRC

Confirmed
- Field reversal
- Long pulse stability
- Electron heating (100 eV bulk and 700 eV tail with 20 kW)

In Progress
- Raise power and field (200 kW and 0.1 T)
- Lower frequency
- Heat ions
- STTR: magnets
- ARPA-E: heating

Next Steps
- High field operation
- Particle exhaust
- Demonstrate fusion

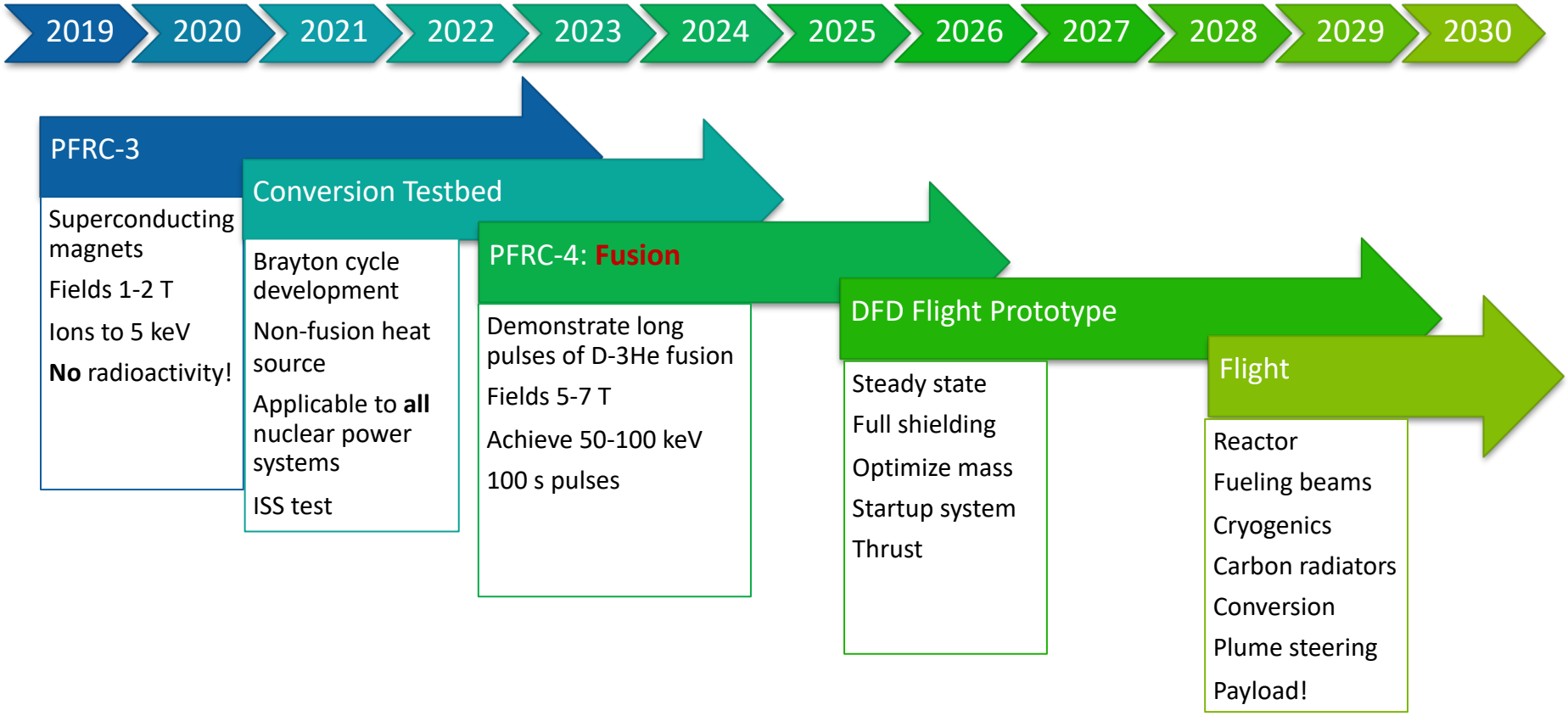


Machine	PFRC-1	PFRC-2	PFRC-3	PFRC-4
Objectives	Electron Heating	Ion Heating	Heating above 5 keV	D-He3 Fusion
Fuel	H	H	H, D	D-3He
Goals/ Achievements*	3 ms pulse* 0.15 kG field* e-temp = 0.3 keV* RF power = 10 kW	0.3 s pulse* 1.2 kG field e-temp = 0.5 keV* i-temp = 1 keV RF power = 30*/200 kW	10 s pulse 10 kG field i-temp = 5 keV	1000 s pulse 60 kG field i-temp = 50 keV RF power = 1 MW
Plasma Radius	4 cm	8 cm	16 cm	25 cm
Time Frame	2008-2011	2011-2020	2020-2023	2023-2025

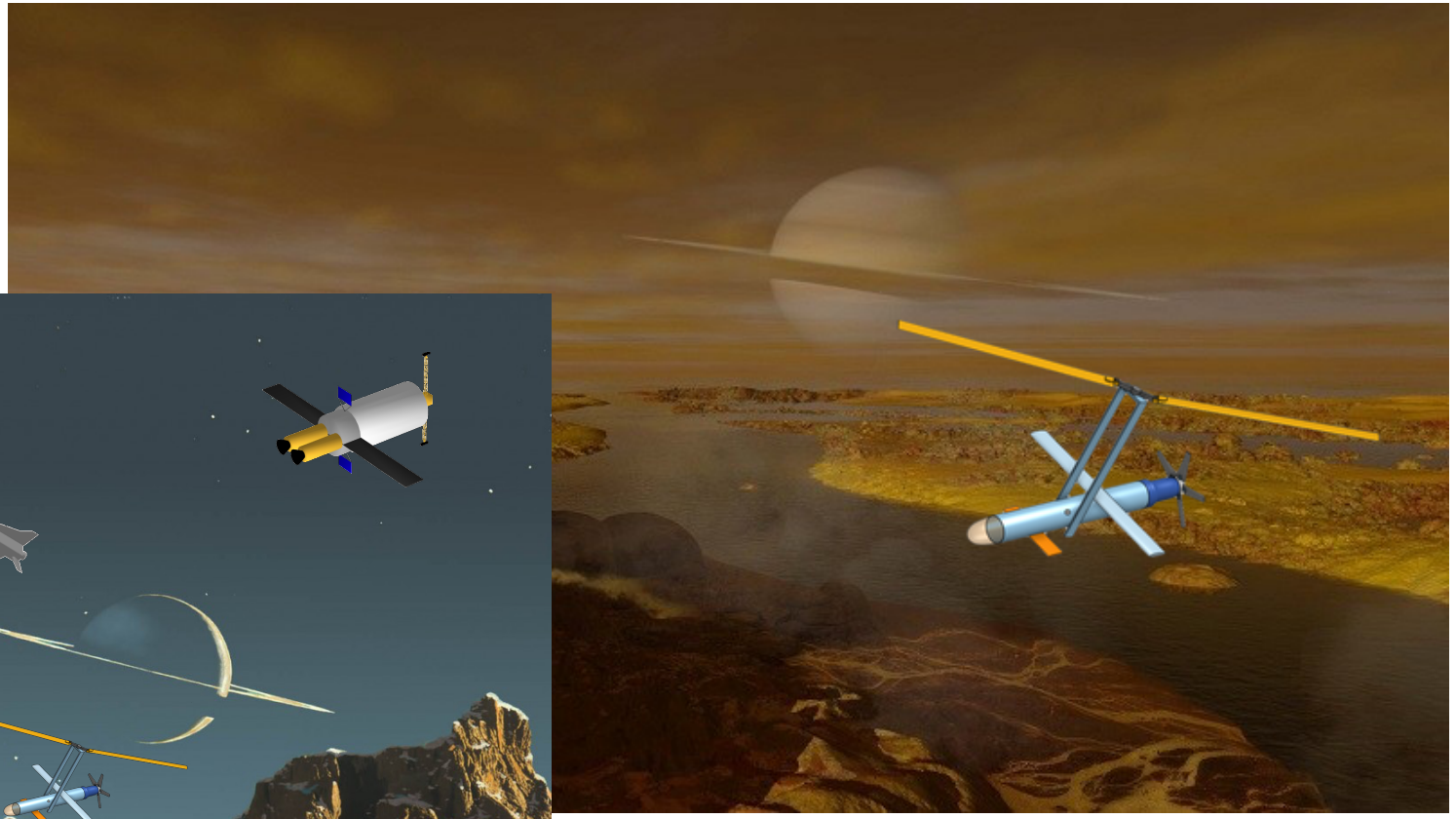
Key Enabling Innovations for Space

PFRC	Magnets	Heat Engine	Radiators	Cryogenics
Compact	"dry" cooling of LTS	High-temp Ceramics	Carbon-carbon	Lightweight tanks
1-10 MW "mini" reactor	2nd gen HTS	Electric Transmission	Woven fiber fins	New coatings
Low radioactivity		Carbon-carbon recuperator		

Notional Roadmap to Flight



Mission Concept: Titan Autogyro



Mission Concept: Solar Gravitational Lens

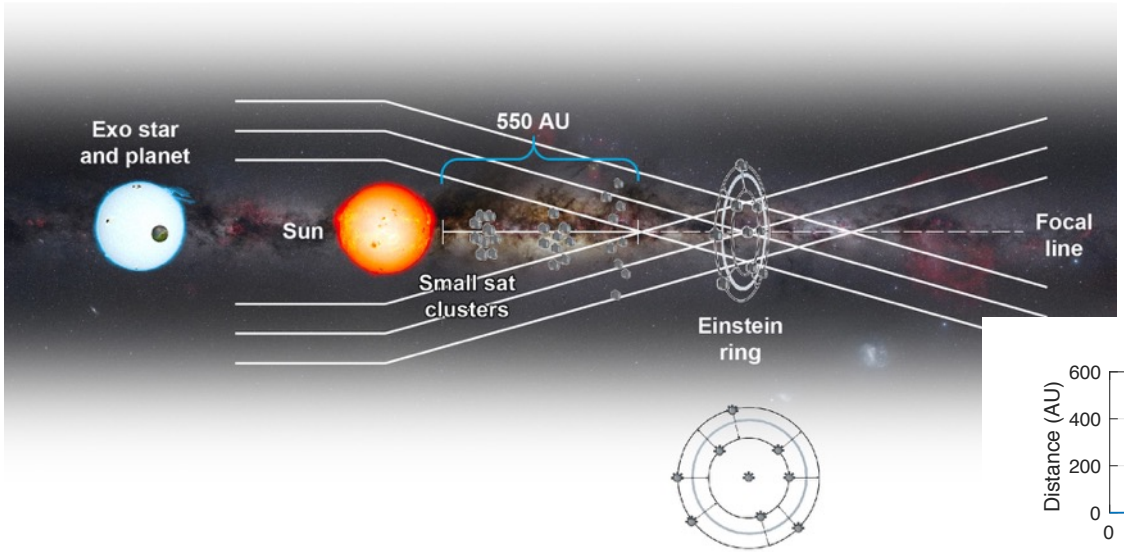
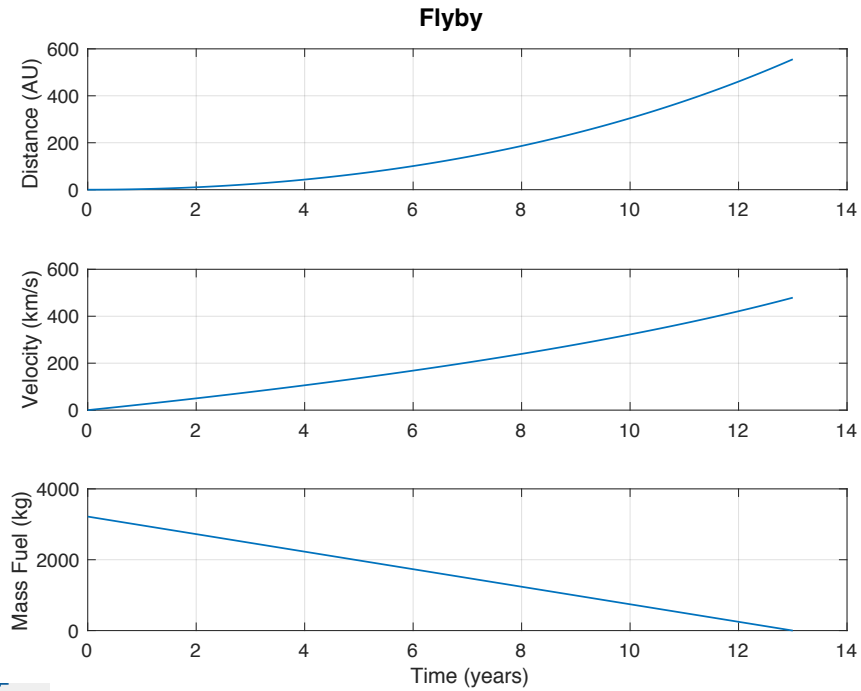


Image: Aerospace Corp.

Deliver telescope in < 15 years



Princeton Satellite Systems

Thank You

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Your favorite mission is better with a fusion engine!

Solar gravitational lens

Saturn

Cislunar space gateway

Mars base

Uranus

Pluto orbiter and lander

Lunar base

Titan

Asteroid defense

High-power Earth satellites

Europa

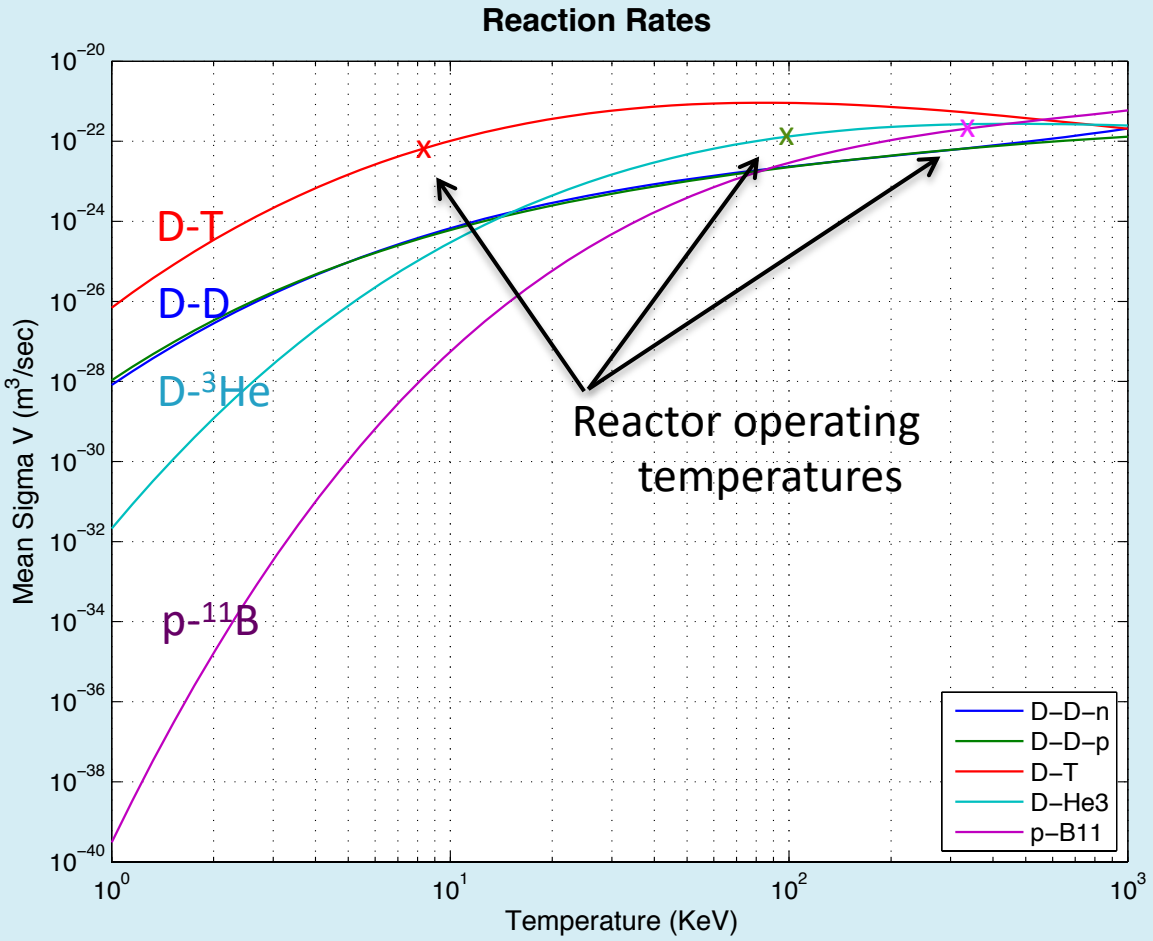
Neptune

Interstellar precursor

Backup Slides

ADDITIONAL TECHNICAL INFORMATION

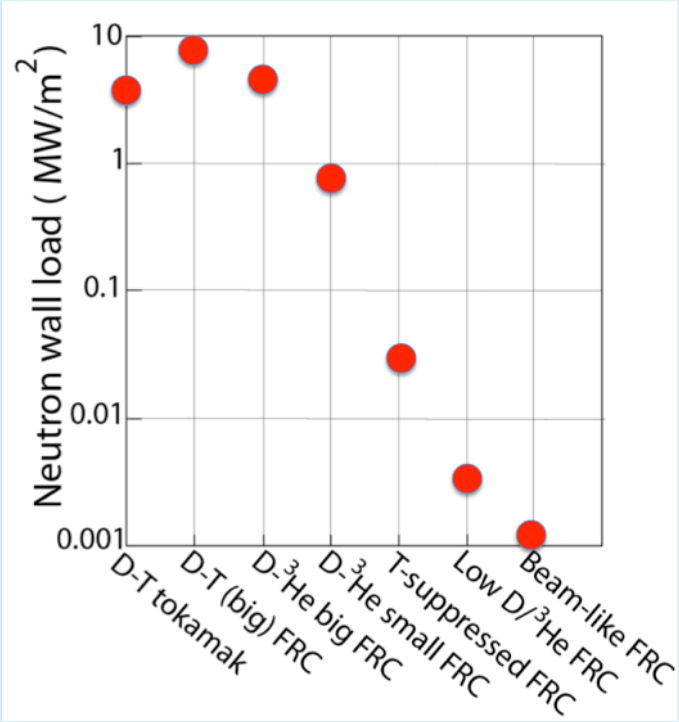
Fusion “Cross-Sections”



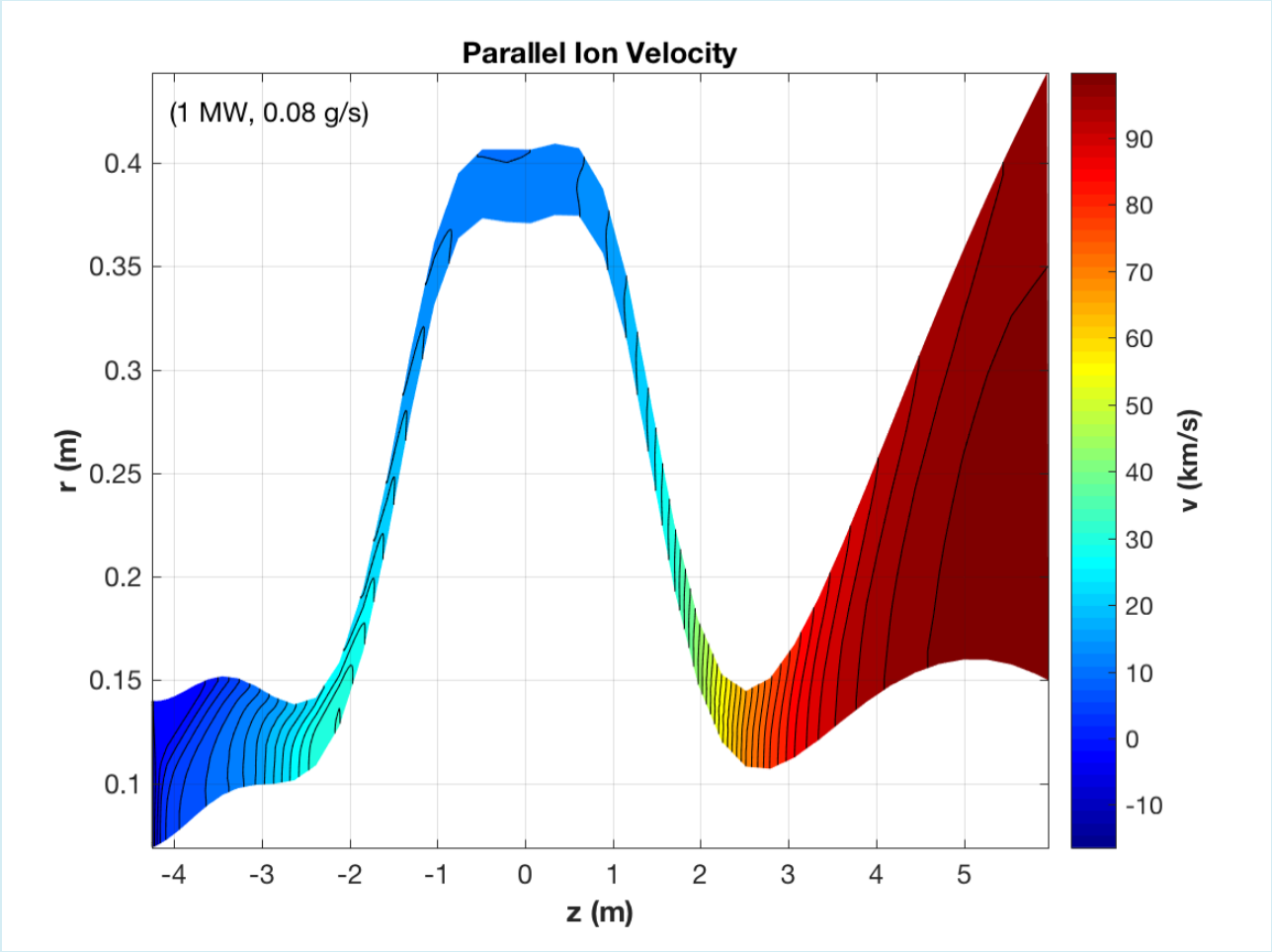
- D-3He requires 10x higher temperature than D-T
- p-B11 requires higher still

Neutron Reduction Mechanisms in the PFRC

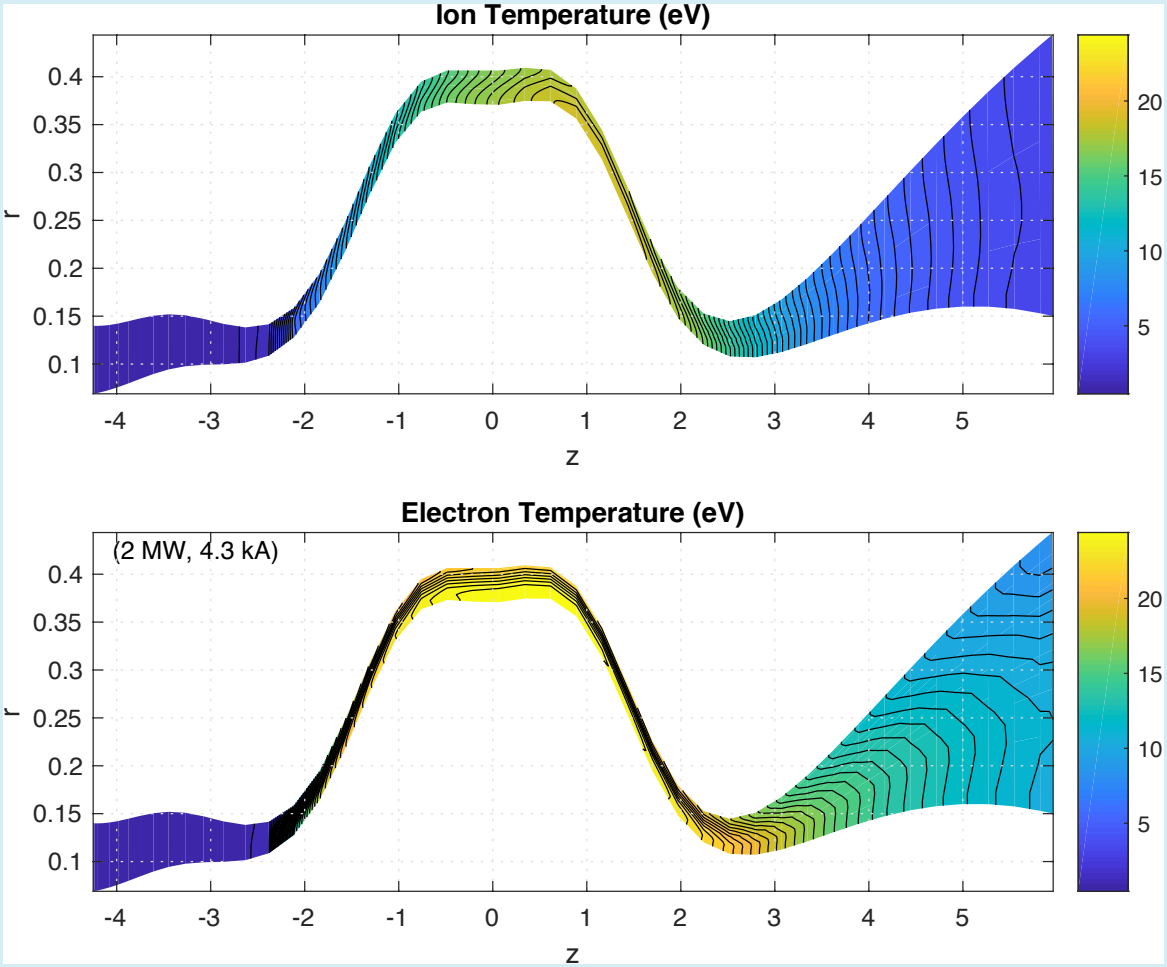
1. Tokamak -> FRC
   - Neutron load actually WORSE
2. Fuel – D-^{3}He
3. Size – small radius FRC
   - First big reduction in overall load
4. Fast removal of tritium in scrape-off layer
5. Low D fuel ratio:
   - D/^{3}He of 1:3
6. Non-equilibrium:
   - D heating only ½ as much as ^{3}He by ω_{RMF}
   - Beam-like distributions



UEDGE Ion Velocity Model



UEDGE Ion and Electron Temperatures



The ions cool off as they accelerate down the magnetic nozzle.

The electrons carry some thermal energy with them.