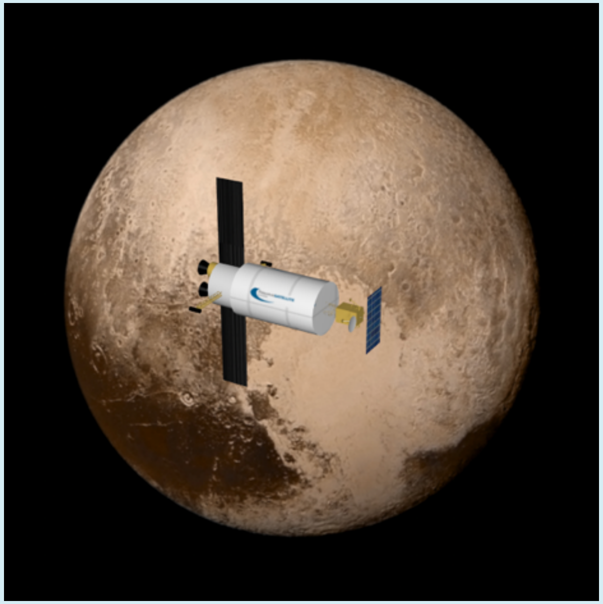
Fusion-Enabled Pluto Orbiter and Lander

US-Japan CT 2016

August 22-24

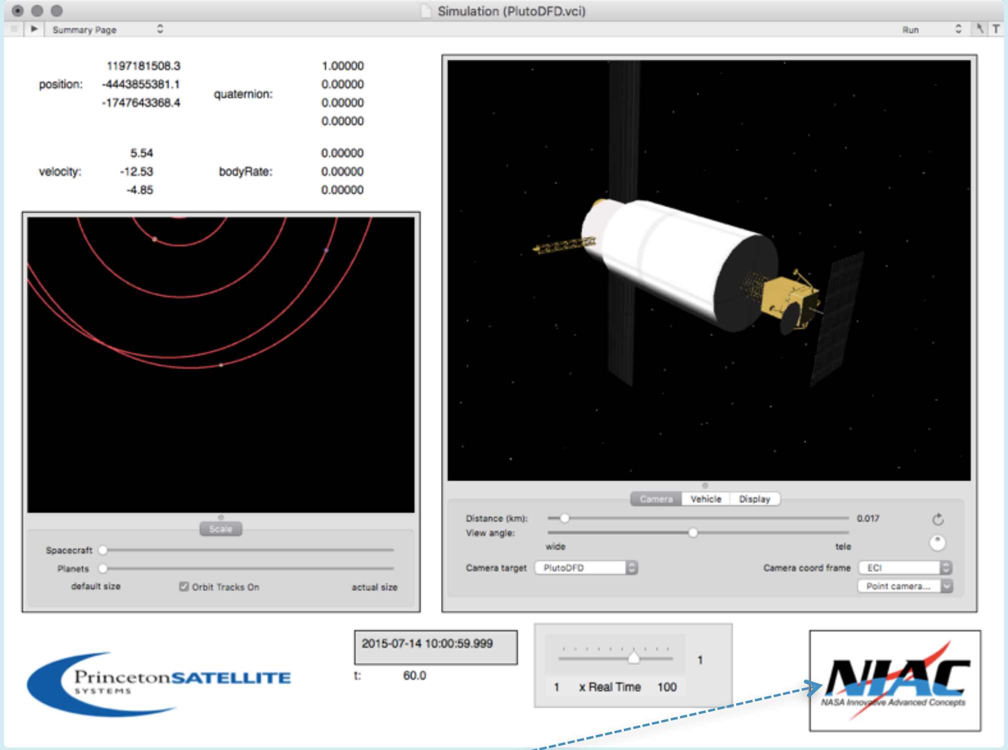


Michael Paluszek
Princeton Satellite Systems, Inc.

Outline of Talk

- Electric propulsion
- Pluto mission overview
- Mission design
- Spacecraft design
- DFD overview and status
  - FRC with odd-parity RF heating
  - D – ^{3}He fuel
- DFD subsystems
- Work in progress and conclusions

Simulation of DFD Pluto Approach



position: 1197181508.3 -4443855381.1 -1747643368.4

quaternion: 1.00000 0.00000 0.00000 0.00000

velocity: 5.54 -12.53 -4.85

bodyRate: 0.00000 0.00000 0.00000

Camera target: PlutoDFD

Camera coord frame: ECI

2015-07-14 10:00:59.999

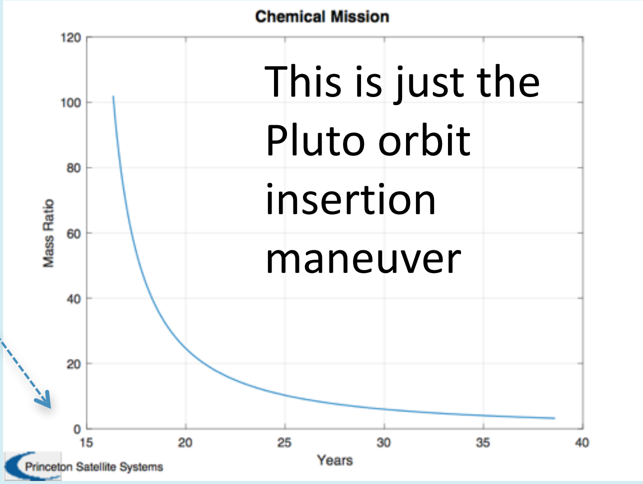
t: 60.0

Supported by NASA Innovative Advanced Concepts Program under award NNX16AK28G

Electric Propulsion

- Critical relations
  - Power/thrust relationship
  - Rocket equation with specific power
- Specific power is the key to performance
  - Ratio of power in the thrust to engine mass
- Exhaust velocity determines achievable velocity change

DFD gets to Pluto in 4 years



This is just the Pluto orbit insertion maneuver

Thrust

$$P = \frac{1}{2}\frac{T u_e}{\eta}$$

Mass of fuel

$$\frac{m_f}{m_p} = \frac{\gamma - 1}{1 + f_s - \gamma f_s}$$

Total velocity change

$$\gamma = e^{\frac{\Delta u}{u_e}}$$

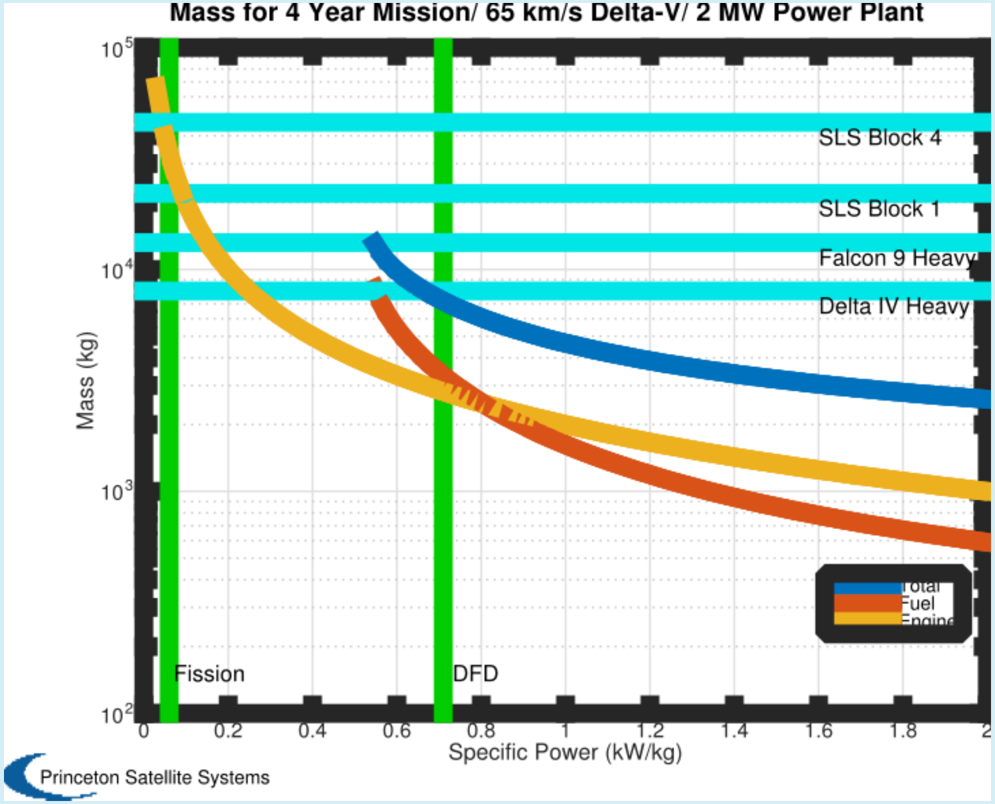
Exhaust velocity of engine

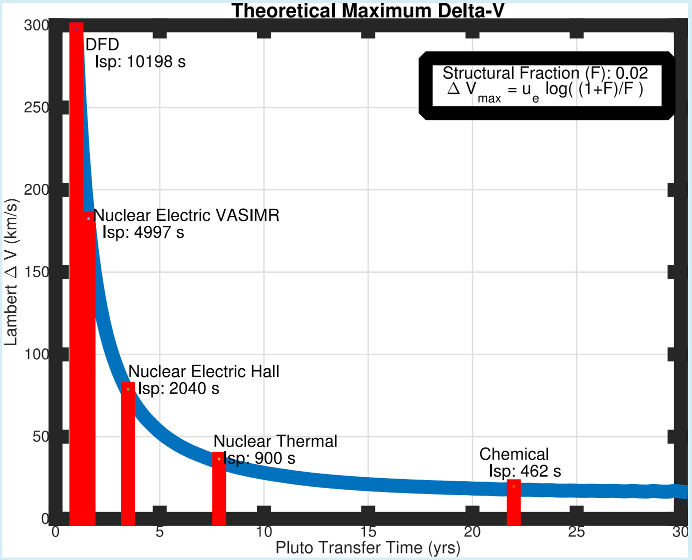
Fraction of mass proportional to fuel

Mass of payload and engine

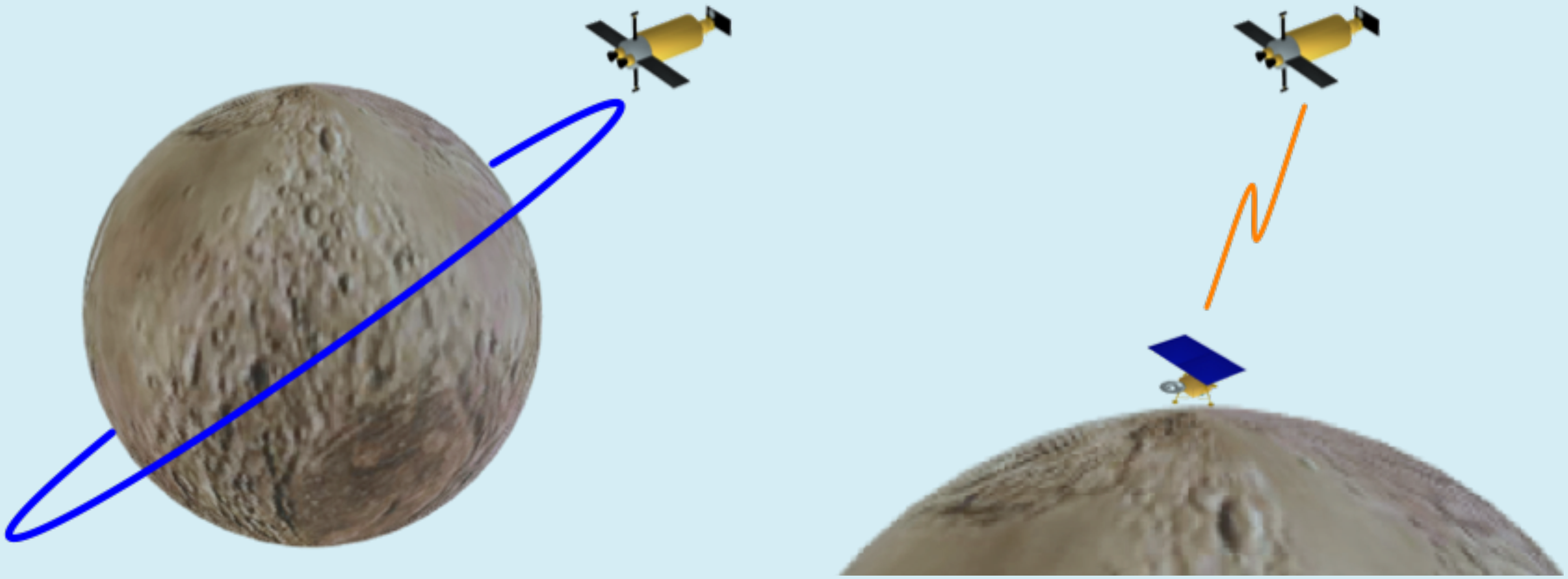
Specific Power

- Plot on right based on work done assuming direct insertion
- Other electric propulsion systems
  - Solar – not applicable to outer planet missions
  - Fission Electric





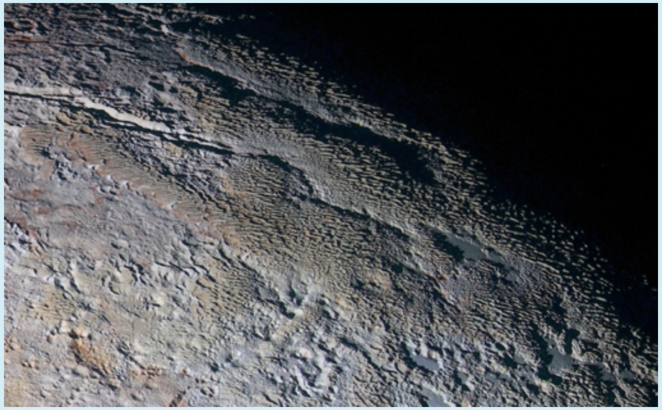
Destination: Pluto Orbit

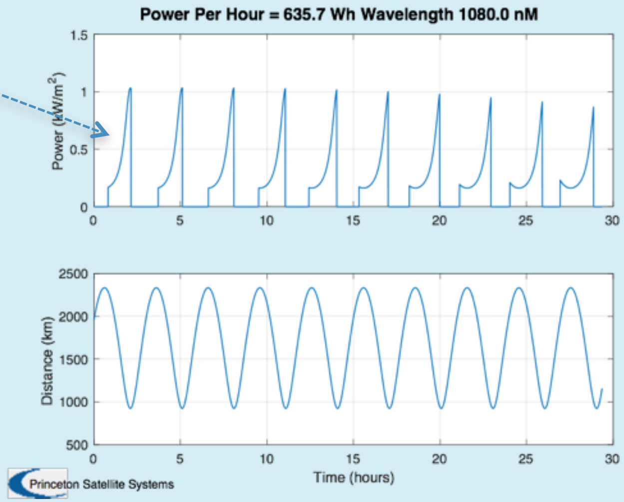


Put a spacecraft in orbit around Pluto, power a lander using optical transmission, return high-definition video – and get there in only **4 years**!

Pluto Mission

- Deliver payload 1000 kg of orbiter and lander
- 1158 L of ^{3}He for the entire mission
- Arrives in just 4 years
- Provides 2 MW of electrical power
  - Beam 30 kW down to lander
- Launch mass can be accommodated by almost any launch vehicle
- ^{3}He fuel can be purchased in sufficient quantities now from available suppliers





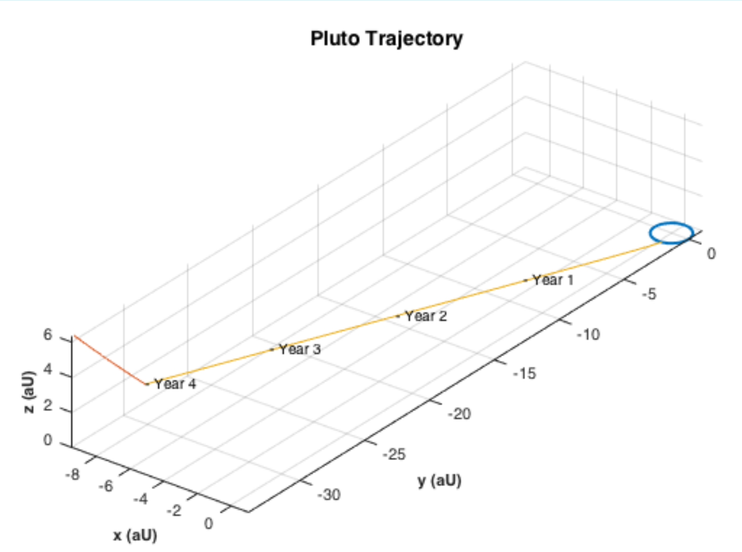
Pluto Mission Comparison

Parameter	New Horizons	DFD Mission
Travel time to Pluto	9.5 years	4 years
Delta-V	290 m/s	70,000 m/s
Power at Pluto	200 W	2,000,000 W
Data rate to Earth	1 kbit/s	> 1,000,000 kbit/s
Fuel	Plutonium	D-^{3}He
Trajectory	Jupiter Swingby	Direct
Mission type	Flyby	Orbit
Lander	No	Yes

Bottom Line: You can't do the proposed mission to Pluto with any other technology.

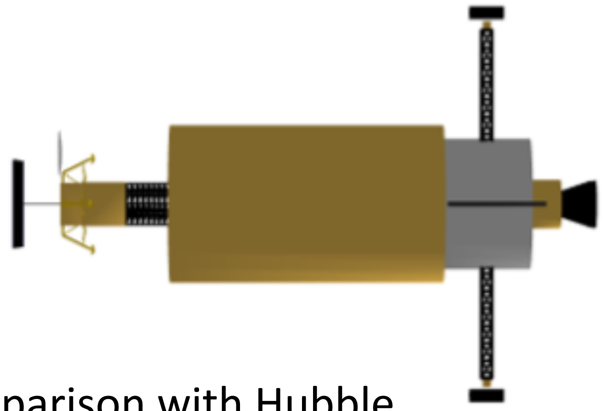
Mission Outline

- Earth departure
- Acceleration – Coast – Deceleration
  - Depends on available thrust
- Insertion into Pluto flyby orbit
- Orbit insertion
- Orbit operations
  - Lander deployment
  - Pluto observations
  - Lander power from orbit

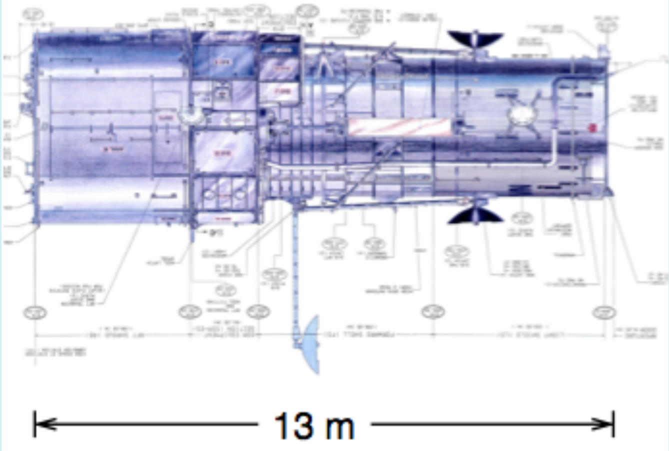


Spacecraft

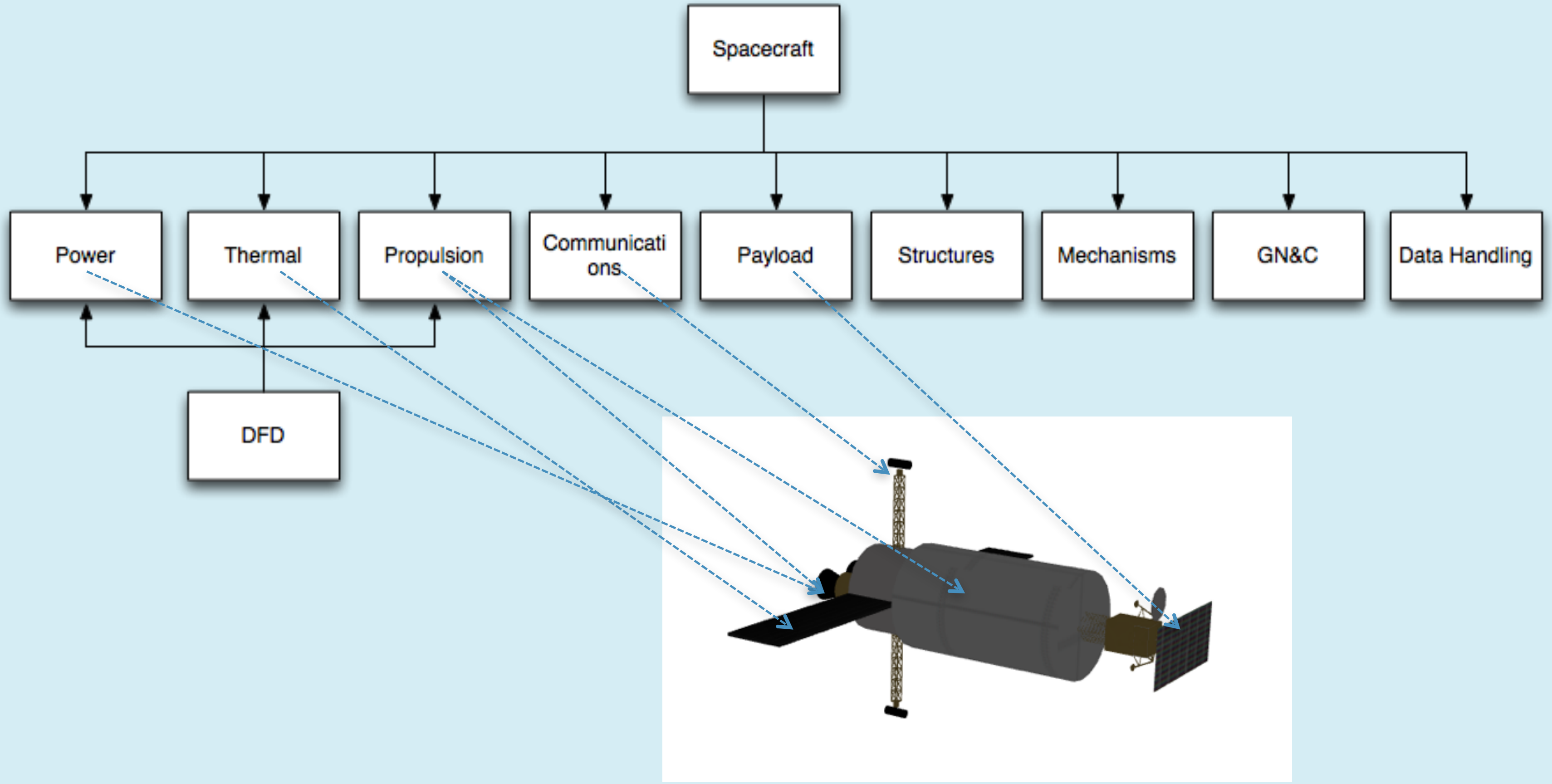
- Wide range of scientific instruments for Pluto orbit survey and a lander
- Large radiators for waste heat rejection
- Cylindrical structure is sun shade with MLI
- Optical communications for HDTV bandwidth to Earth
- Fully autonomous guidance, navigation and control



Comparison with Hubble Space Telescope



Spacecraft Subsystems



Spacecraft

Power

Thermal

Propulsion

Communications

Payload

Structures

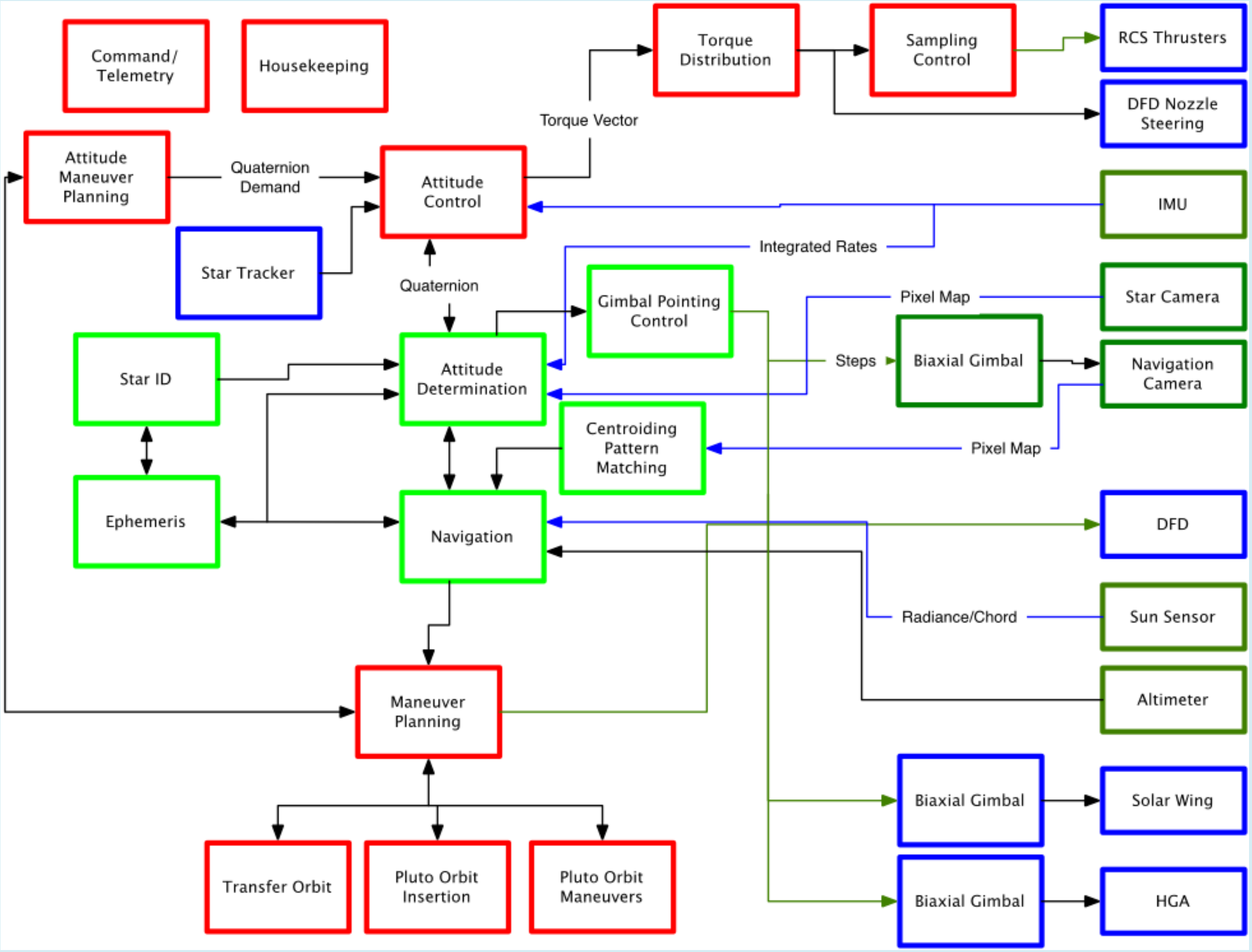
Mechanisms

GN&C

Data Handling

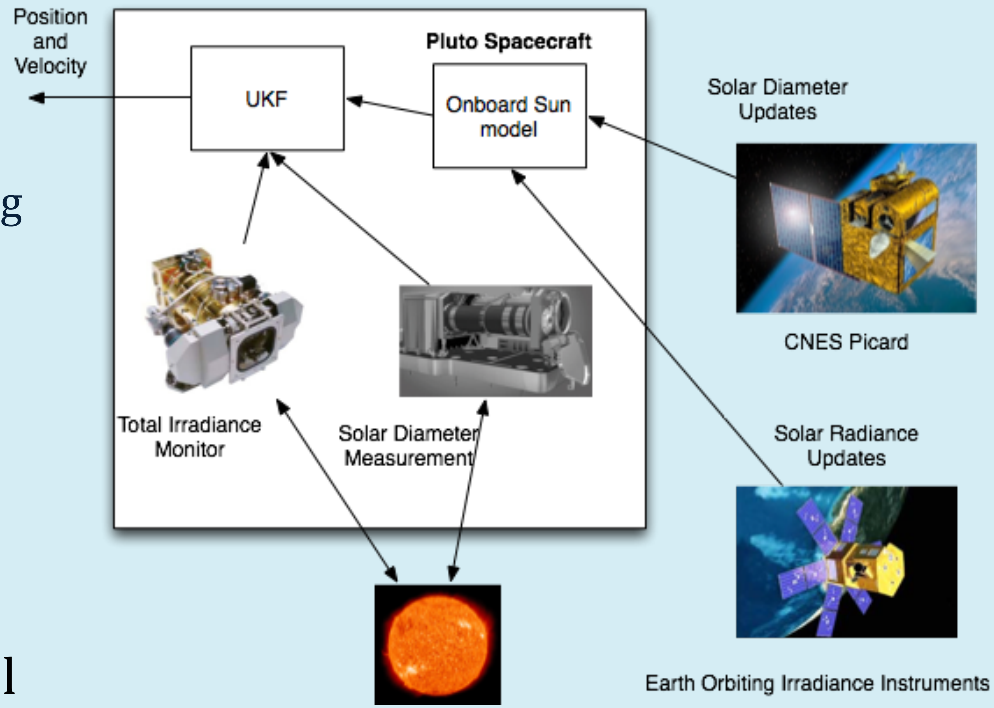
DFD

Guidance, Navigation and Control (GN&C)



GN&C

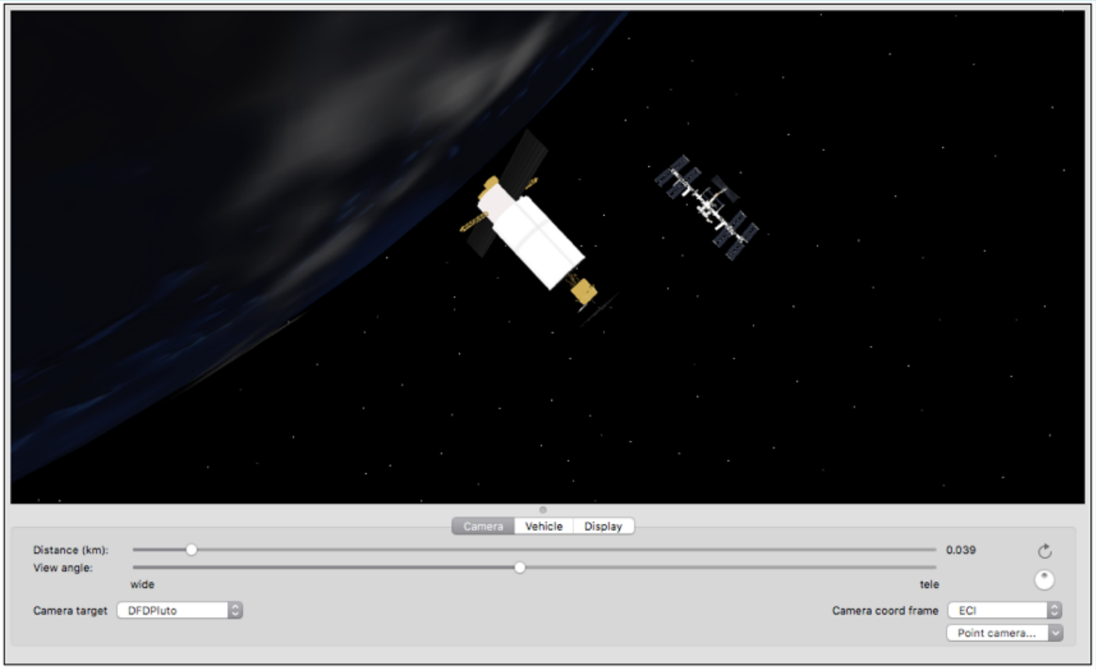
- Optical navigation used throughout
  - Reduces reliance on Deep Space Network
  - Provides continuous updates during burns
  - Operates in heliocentric or Pluto centric modes
- Reaction wheels for attitude control
- Steered plasma plumes for pitch and yaw momentum unloading and control during burns
- Attitude control thrusters for roll control and unloading



UKF is Unscented Kalman Filter

Departure from Earth

- Two options
    - Direct insertion into heliocentric trajectory
    - Departure from LEO
- Direct insertion (rocket puts the vehicle directly into heliocentric orbit) requires Delta IV Heavy class launcher
    - $350M launch cost
- Departure from low earth parking orbit
    - $60M launch cost
    - Requires additional fuel
    - Allows for on-orbit checkout



Distance (km): 0.039

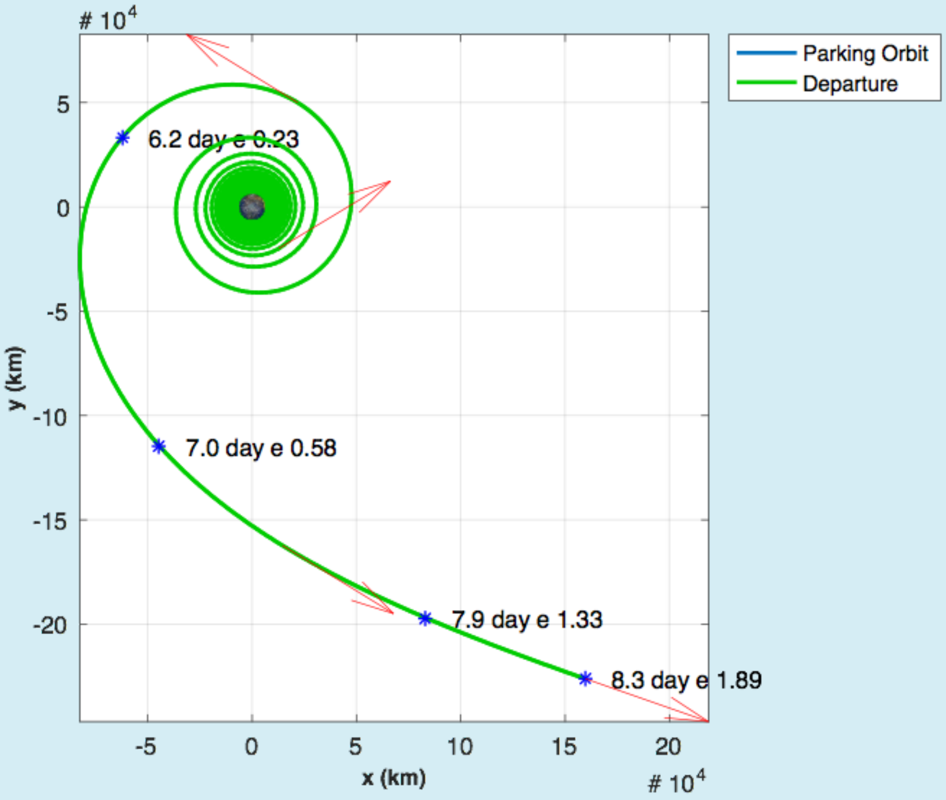
Camera target DFDPluto

Camera coord frame ECI

Simulation of DFD Pluto Vehicle near ISS prior to departure

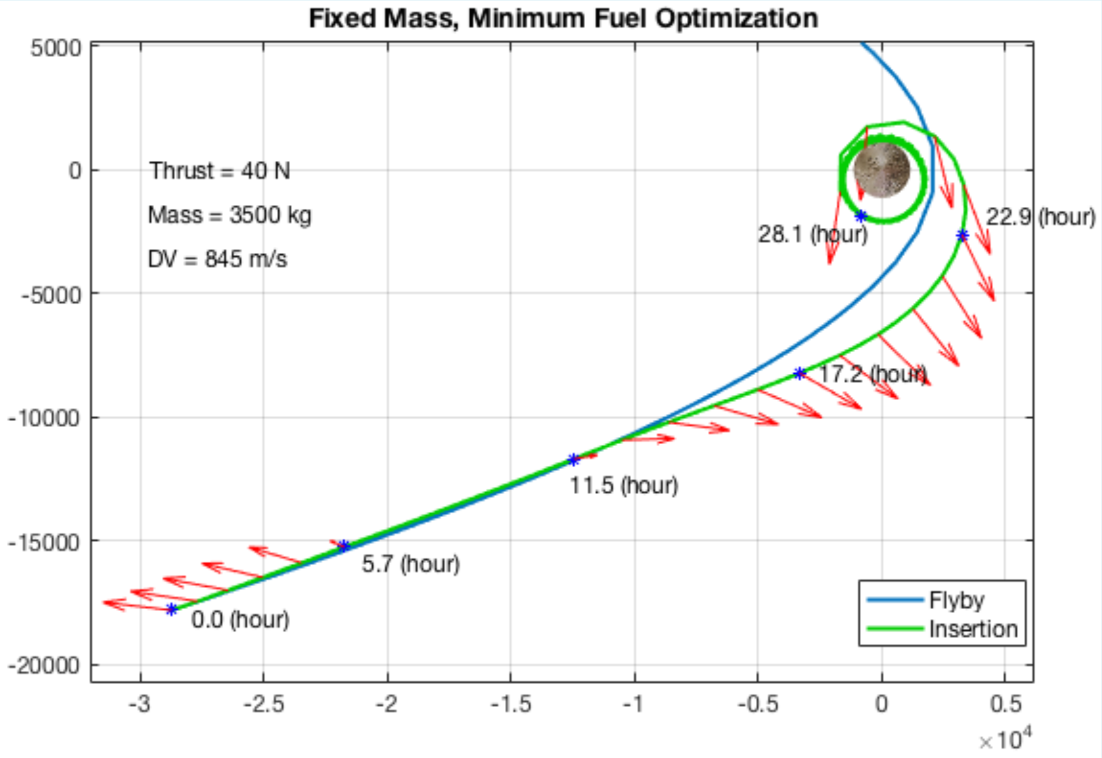
Departure Trajectory

- Assume ISS orbit
  - Allows astronaut checkout prior to departure
- Burn along velocity vector
  - Not optimal
- 40 N thrust assumed
- Orbit becomes hyperbolic in 7.5 days
  - e is orbit eccentricity
  - > 1 is hyperbolic
- Major cost savings
- On-orbit checkout reduces mission risk



Arrival at Pluto

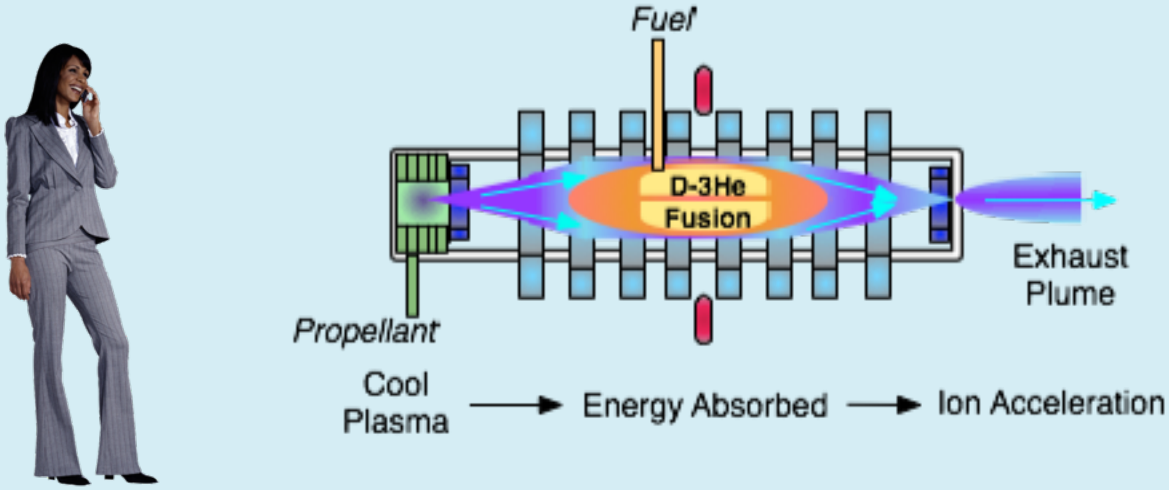
- Optimal trajectory
  - Uses MATLAB’s fmincon
    - Brute force direct method
    - There are other methods
  - Two dimensional problem
  - Inequality constraint on acceleration magnitude
  - Starts in flyby hyperbola
  - Uses twice the velocity change of an impulsive burn at closest approach



Princeton Field Reversed Configuration (PFRC)

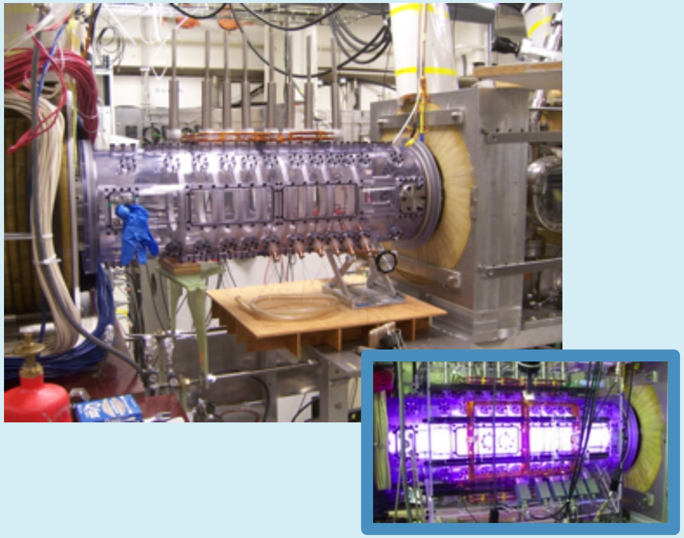
- RF heating with rotating magnetic fields naturally limits reactor size
  - Plasma radius in range 20-40 cm
  - Power of 1-10 MW is ideal for space
- Confinement with superconducting coils
- Ultra low radiation

- Linear configuration allows for configuration as a rocket engine
- Flow more D^+ to augment thrust
- Exit via magnetic nozzle
- Variable exhaust velocity
  - 50 to 20,000 km/s
  - $P = 0.5\ Tu_e/\eta$, thrust ~ 10-50 N



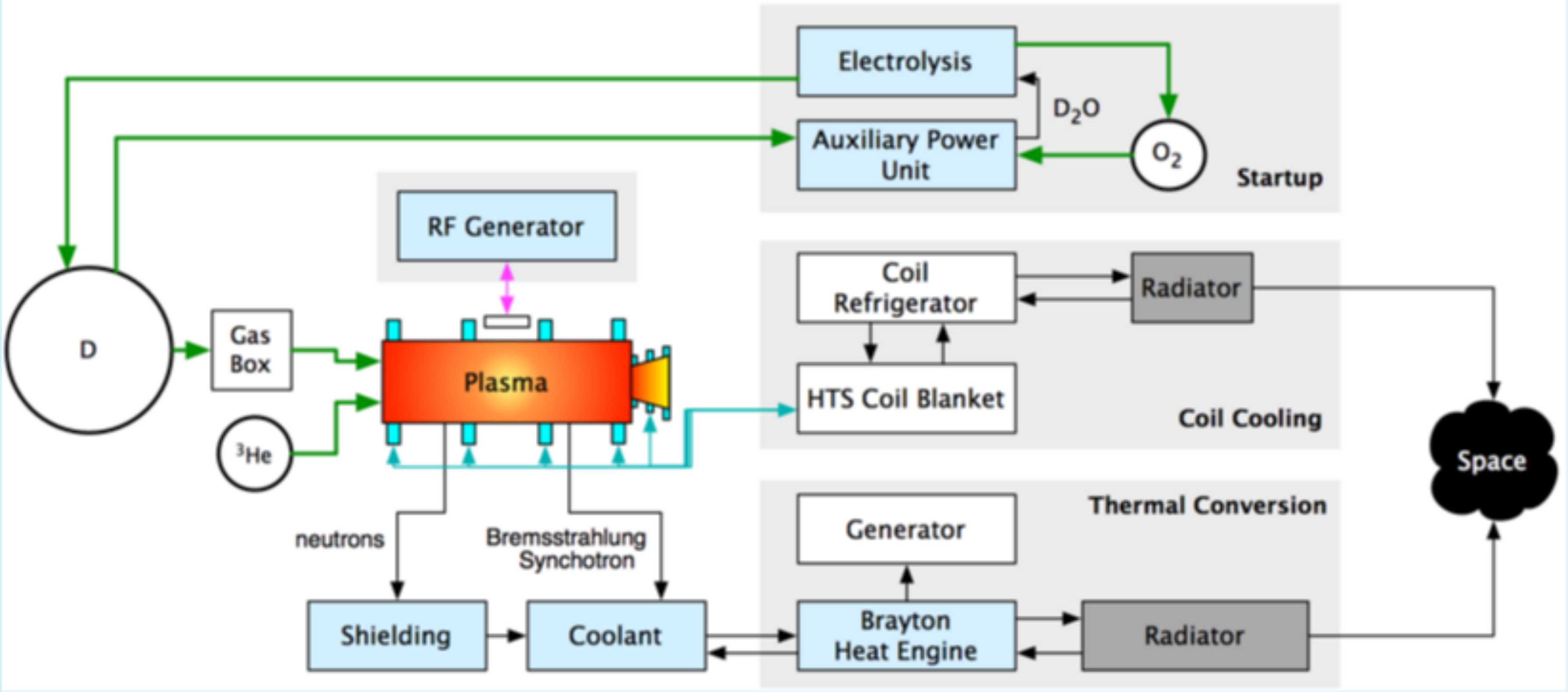
Status of PFRC Development

- Princeton Plasma Physics Laboratory performing experiments with Dept. of Energy funding
  - Concluded PFRC-1 a, b, c in 2011
  - PFRC-2 operating now; goal to demonstrate keV plasmas with pulse lengths to 0.3 s
  - Computational studies on plasma detachment in nozzle
- Princeton Satellite Systems performing mission and trajectory design, space balance of plant studies under IR&D and now NIAC
  - Four joint PPPL/PSS patents

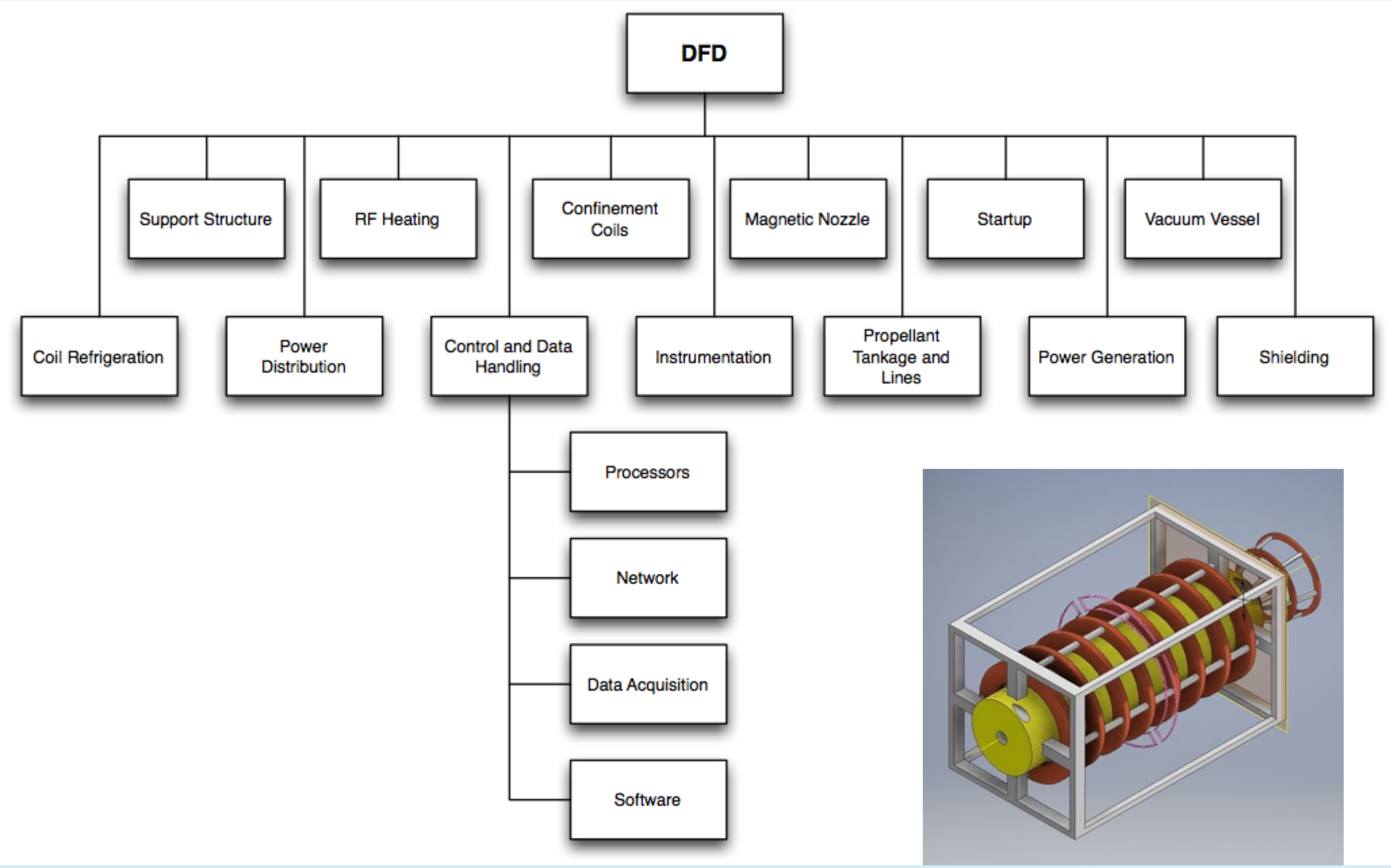


Machine	PFRC-1	PFRC-2	PFRC-3A	PFRC-3B
Objectives	Electron Heating	Ion Heating	Heating above 5 keV	D-He3 Fusion
Fuel	H	H	H	D-3He
Goals/ Achievements*	3 ms pulse* 0.15 kG field* e-temp = 0.3 keV*	0.1 s pulse* 1.2 kG field i-temp = 1 keV	10 s pulse 10 kG field i-temp = 5 keV	10 s pulse 80 kG field i-temp = 50 keV
Plasma Radius	4 cm	8 cm	16 cm	16 cm
Time Frame	2008-2011	2011-2017	2018-2022	2022-2026
Cost	$2M	$4M	$25M	$25M

DFD Diagram


Electrolysis
D_2O
Auxiliary Power Unit
O_2
Startup
RF Generator
D
Gas Box
Plasma
^3He
Coil Refrigerator
Radiator
HTS Coil Blanket
Coil Cooling
Space
Thermal Conversion
Generator
neutrons
Bremsstrahlung
Synchotron
Shielding
Coolant
Brayton Heat Engine
Radiator

DFD Subsystems



DFD

Support Structure

RF Heating

Confinement Coils

Magnetic Nozzle

Startup

Vacuum Vessel

Coil Refrigeration

Power Distribution

Control and Data Handling

Instrumentation

Propellant Tankage and Lines

Power Generation

Shielding

Processors

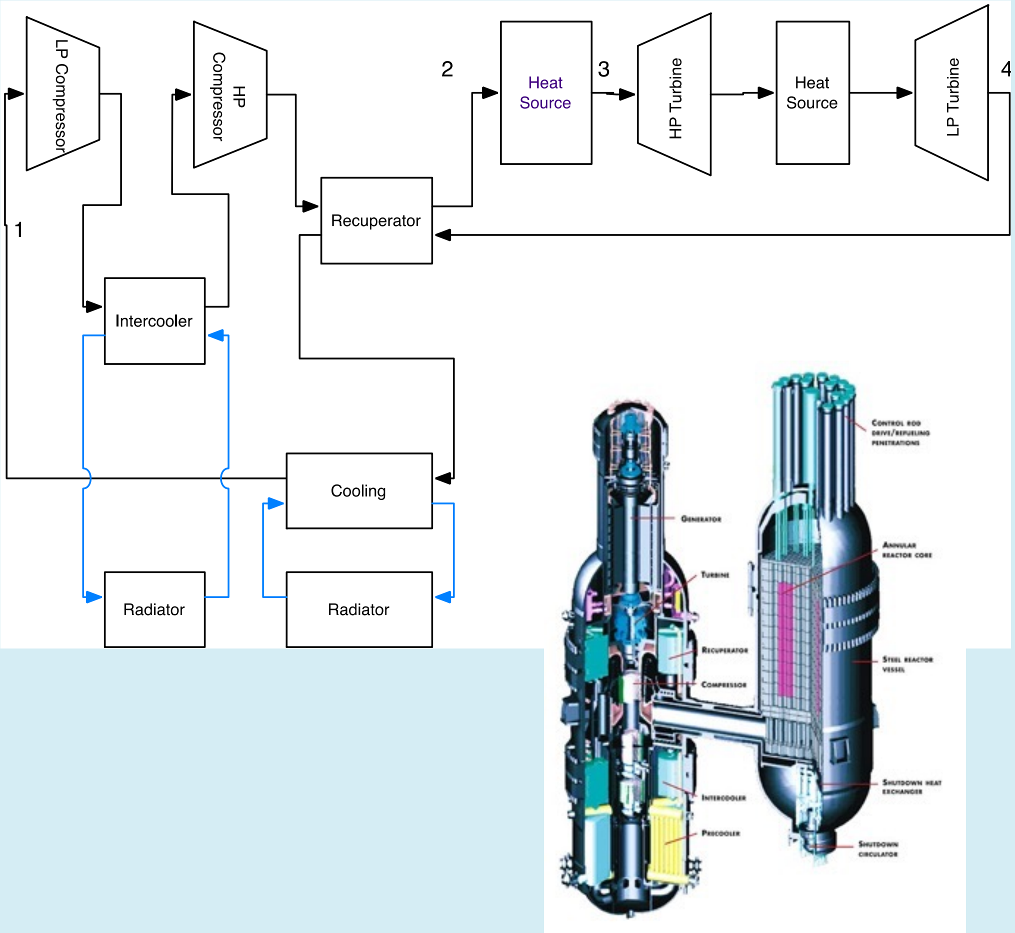
Network

Data Acquisition

Software

Heat Recycling

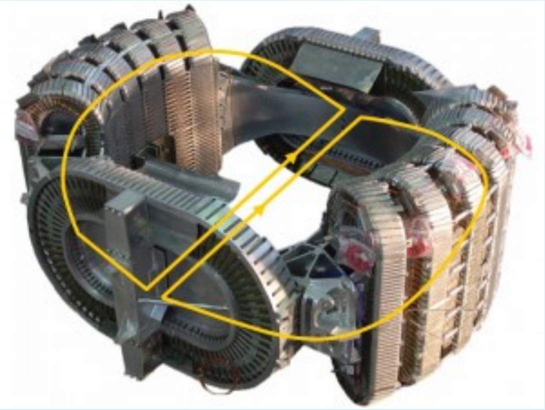
- Brayton cycle heat engine
  - Heat high pressure gas to do work
- Used in High Temperature Gas Cooled Fission Reactors
- Helium working fluid
- Paired compressor/turbine sets with counter-rotating turbines and compressors
- Common shaft for compressor, turbine and generator
- Need for multiple compressor and turbine stages and recuperator to be determined
- Large radiator wings

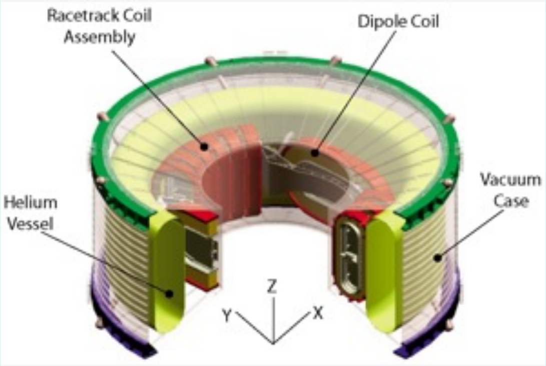


HTGCR

Superconducting Coils Designed for Space

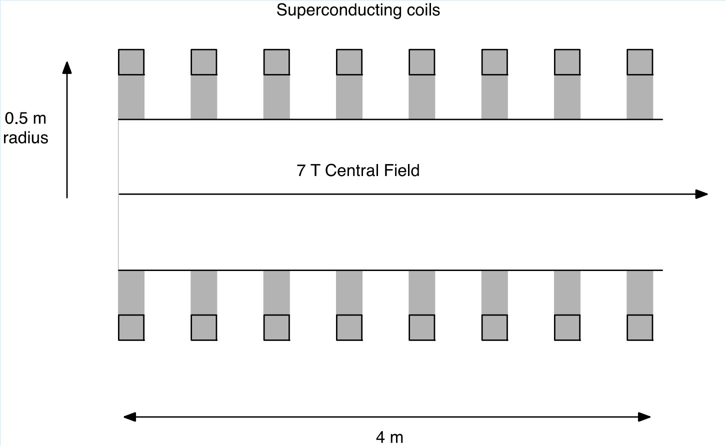
- Alpha Magnetic Spectrometer-02
- Looking for anti-matter and dark matter
- Cooled with superfluid helium

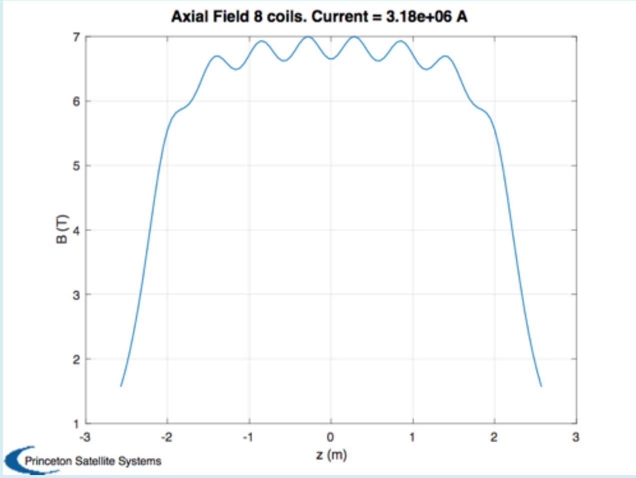




Superconducting Coils

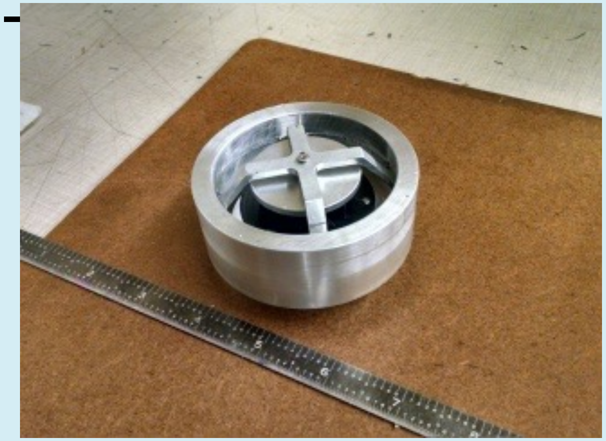
- Eight discrete coils in a 4 m machine
  - Some ripple which would be reduced by the plasma field
- Axial field compatible with HTS and NbTi LTS
- Forces between coils are 5.7 × 10^6 N

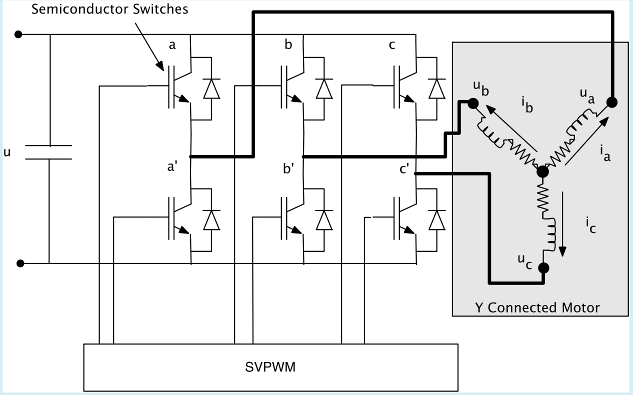




Power Generation and Distribution

- Power generated by a 3 phase axial-flux Halbach Generator
  - Distribution is 3 phase to RF drive
  - 98% efficient at design point
  - AC/DC converters and 3 phase to one phase converters as needed
- A very small Halbach motor/generator developed at Princeton Satellite Systems for an Army satellite

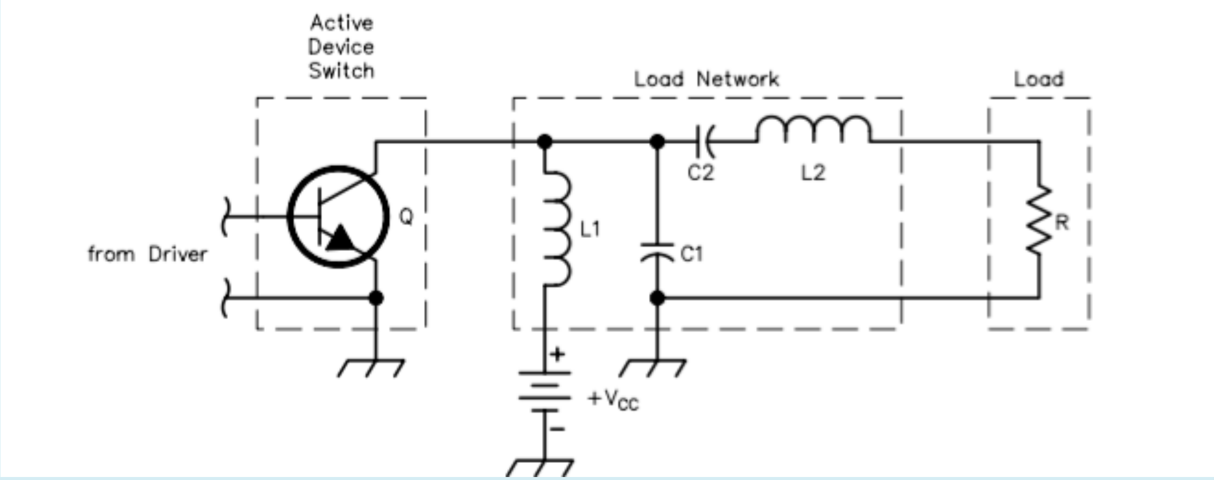




Driver configured as motor

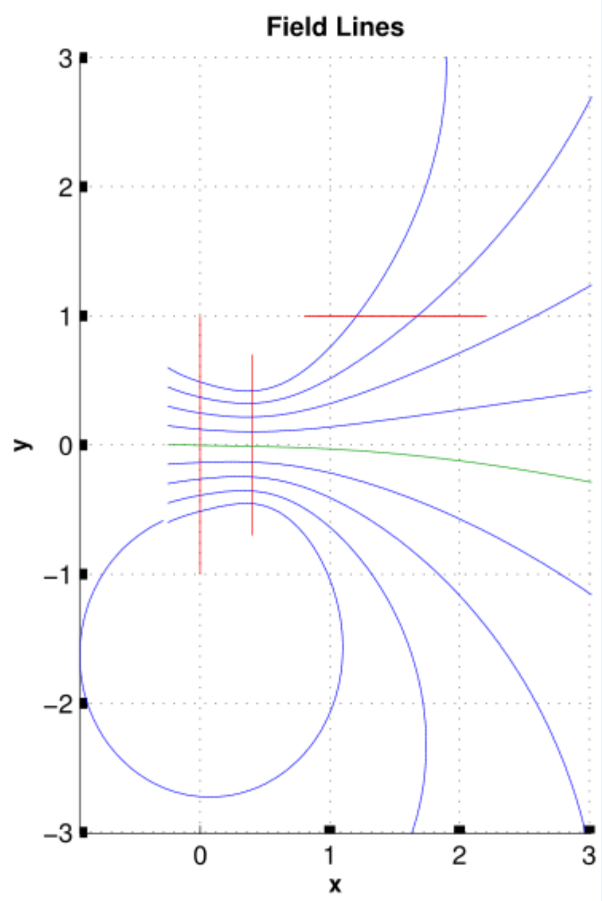
Radio-Frequency Heating

- Odd-parity rotating magnetic field
- Class E power RF amplifiers
  - Transistor operates as on on/off switch
  - Load network shapes waveform so that the current and voltage do not simultaneously peak thus minimized power dissipation (P = IV)



Thrust Vectoring

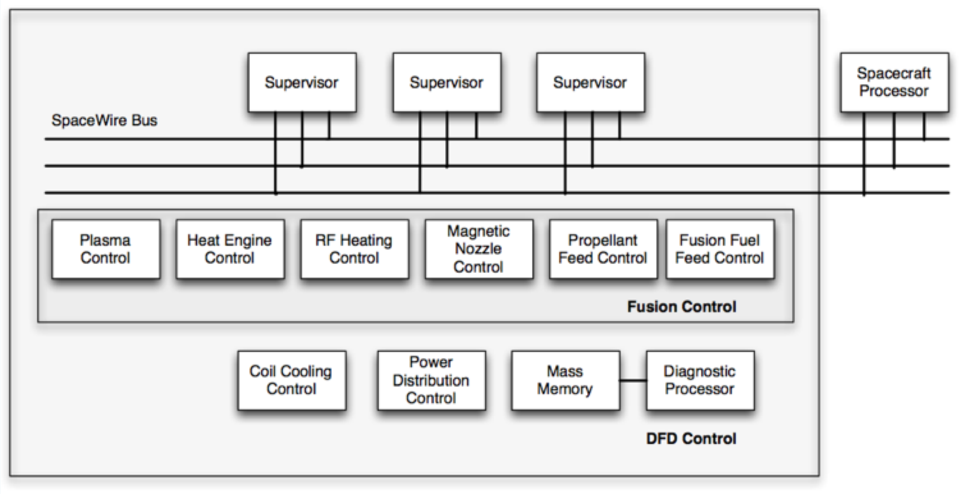
- 1 to 2 degree deflection needed to point thrust vector through the center of mass
- Options
  - Fixed steering coils after the magnetic nozzle
  - Gimbaled engine
  - Moving mass



Field lines as deflected by a steering coil

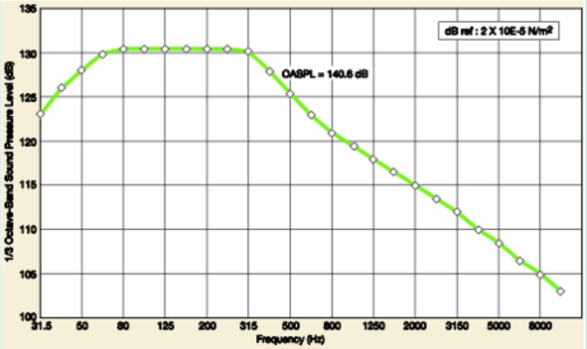
Instrumentation and Control

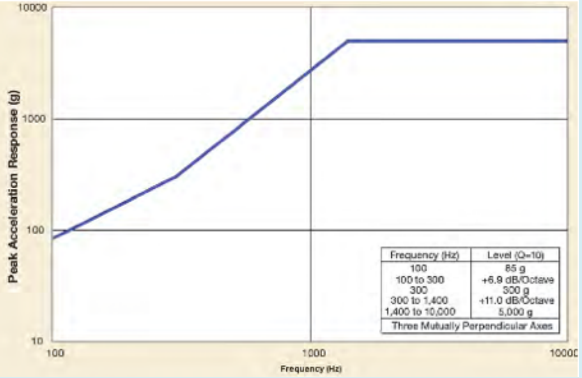
- Triply redundant
- Radiation hard processors
  - BAE 5545 Multi-Core
  - For deep space environment
- Plasma measurements
- Power system measurements
- Interacts with the spacecraft control system
- Uses PPPL Central Instrumentation and Control System (CPCS) data handling system
  - Based on EPICS, Experimental Physics Industrial Control System
  - SpaceWire used for networking



Structure

- Handles launch loads and superconducting coil loads
  - Engine and spacecraft must undergo shock and vibration testing
  - Fuel slosh is a consideration
- Delta IV
  - Launch loads are typically 5-6 g axial
  - Sinusoidal vibration
    - Thrust: 1.27 cm 5 to 6.2 Hz, 1 g 6.2 to 100 Hz
    - Lateral: 0.7 g 5 to 100 Hz
  - Acoustic
  - Shock at separation

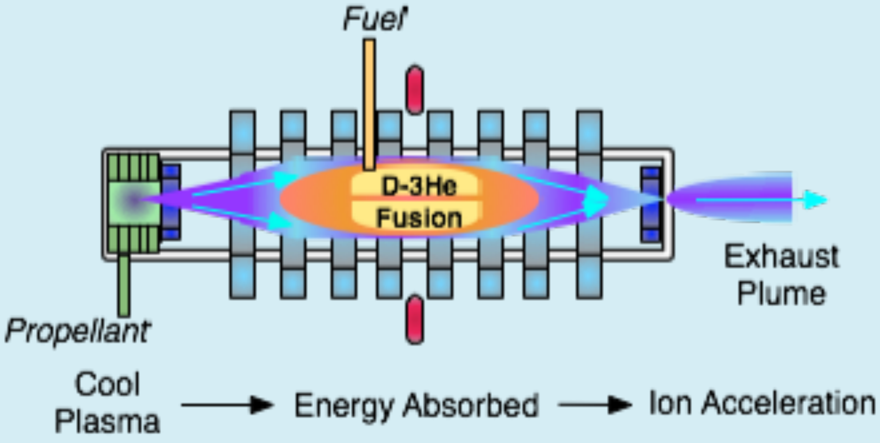




Frequency (Hz)	Level (Q=10)
100	85 g
100 to 300	+6.9 dB/Octave
300	300 g
300 to 1,400	+11.0 dB/Octave
1,400 to 10,000	5,000 g
Three Mutually Perpendicular Axes	

Thrust Augmentation

- H or D is used as a **propellant**- it flows along the magnetic field lines outside of the separatrix; scrape-off layer (SOL) e- are heated by the fusion products that are ejected into the SOL;
  e- energy transferred to ions in plume expansion
- This reduces the exhaust velocity of the fusion products from 25,000 km/s to ~50 km/s and increases thrust to >20 N
- Thrust/I_{sp} is adjustable based on rate that gas is injected into the gas box
- The exhaust plume is directed by a magnetic nozzle, consisting of a throat coil and nozzle coils to accelerate the flow.

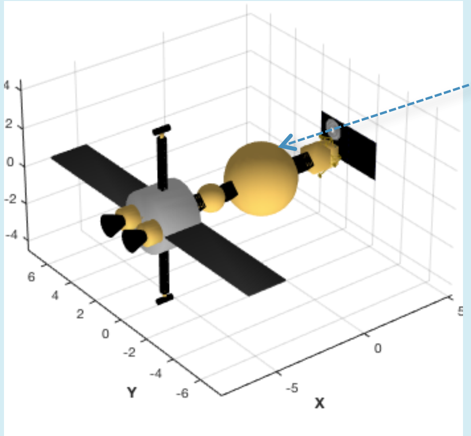


Startup

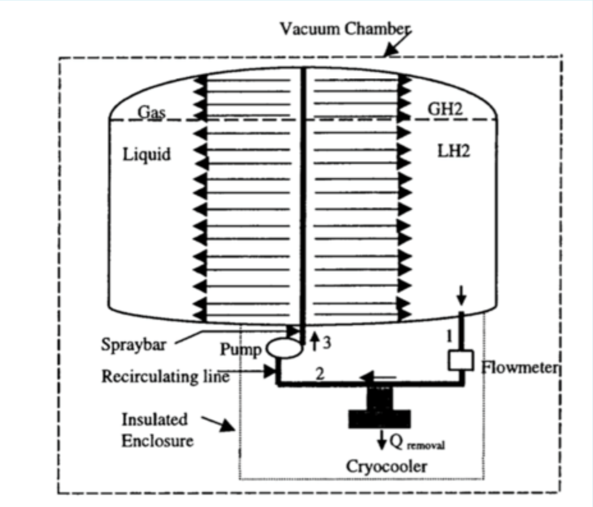
- Fusion engine needs to be started and restarted in space
  - Initiate nuclear fusion
  - Charge the superconducting coils
  - Roughly 100 seconds of power required
- Employs combustor burning D_2 and O_2 carried onboard
  - D_2O can be recycled via electrolysis
    - We have power to spare

Fuel Storage

- Store cryogenic deuterium and helium-3
- Super-insulated tanks and propellant lines
  - Uses Multi-layer Insulation (MLI)
- Cryocoolers to recycle vapor that is not needed for propulsion
  - Same cryocoolers used for coil cooling



Spacecraft without sun shield



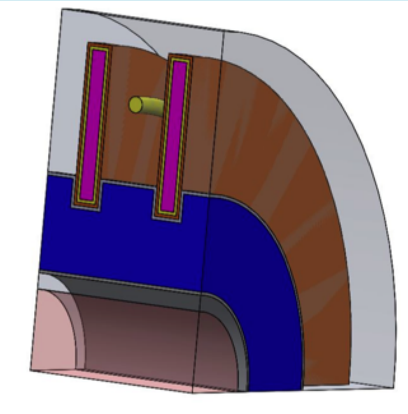
NASA Zero Boil-off Experiment

Vacuum Vessel

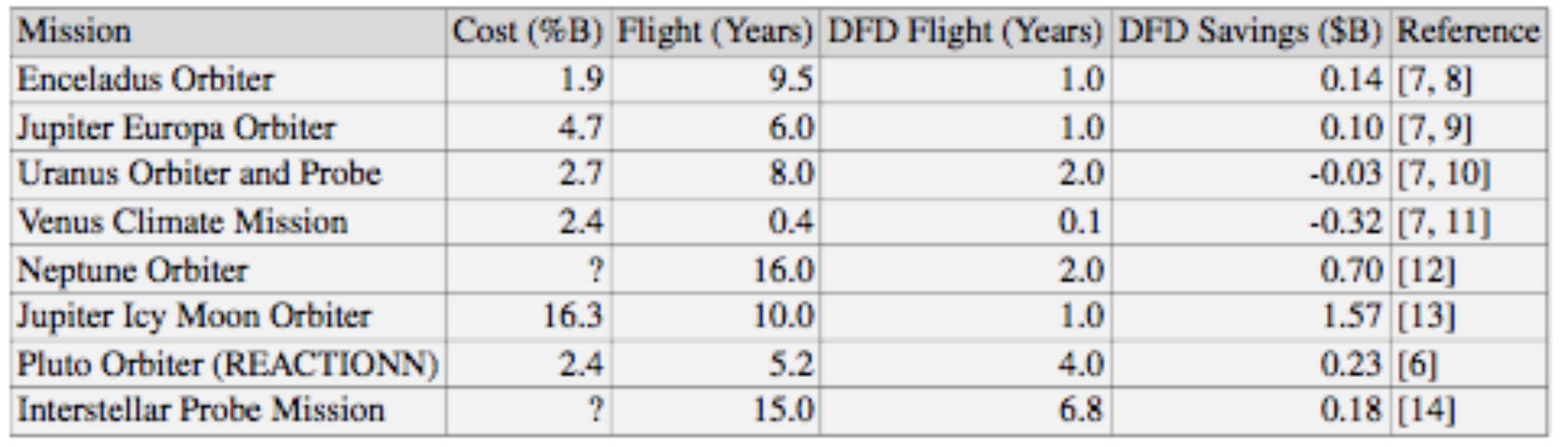
- Presents first wall to plasma
  - Must minimize contamination
- Supports instrumentation
- Keeps spacecraft debris and outgassing outside the fusion chamber
- Pressure differential very small

Shielding

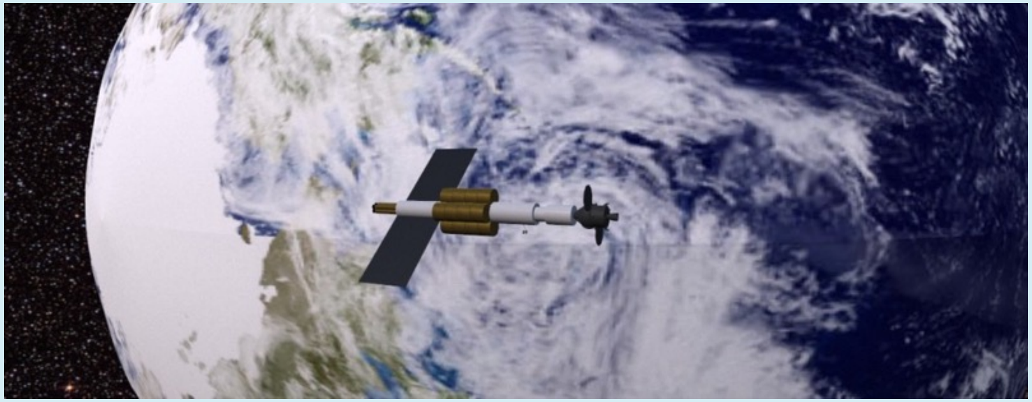
- Protect from neutrons and radiation
  - Superconducting coils are susceptible to neutron damage
- Bremsstrahlung and synchrotron radiation must be recycled for the RMF drive
  - Absorbed by tungsten lining the reactor cooling tubes
- Boron Carbide for neutron shielding
- Some shielding may be required for the payload and for operation in low-earth orbit near astronauts
- Want to minimize shielding
  - Reduces specific power
  - Increases radius of superconducting coils

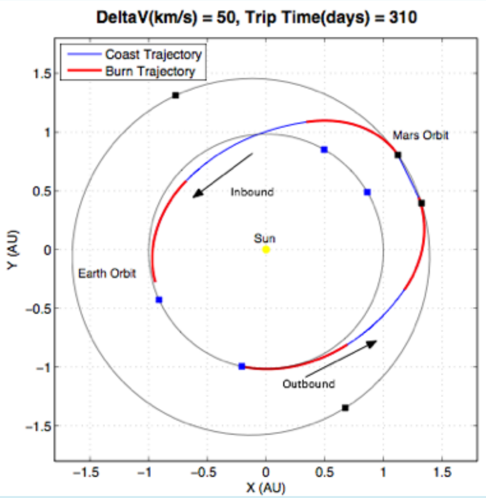


Other Missions



Mission	Cost (%B)	Flight (Years)	DFD Flight (Years)	DFD Savings ($B)	Reference
Enceladus Orbiter	1.9	9.5	1.0	0.14	[7, 8]
Jupiter Europa Orbiter	4.7	6.0	1.0	0.10	[7, 9]
Uranus Orbiter and Probe	2.7	8.0	2.0	-0.03	[7, 10]
Venus Climate Mission	2.4	0.4	0.1	-0.32	[7, 11]
Neptune Orbiter	?	16.0	2.0	0.70	[12]
Jupiter Icy Moon Orbiter	16.3	10.0	1.0	1.57	[13]
Pluto Orbiter (REACTIONN)	2.4	5.2	4.0	0.23	[6]
Interstellar Probe Mission	?	15.0	6.8	0.18	[14]





Mars human orbital mission

Conclusions/Work in Progress

- Specific power is critical
  - Thrust power to mass
  - Total electric plus thrust power to mass
- Thrust/mass determines trip time
- Mass of all subsystems needs to be quantified
- Writing a design document
  - Preliminary design level of information
  - Will allow design to critical design level in next phase