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Modular Aneutronic Fusion Engine for an Alpha-Centauri Mission

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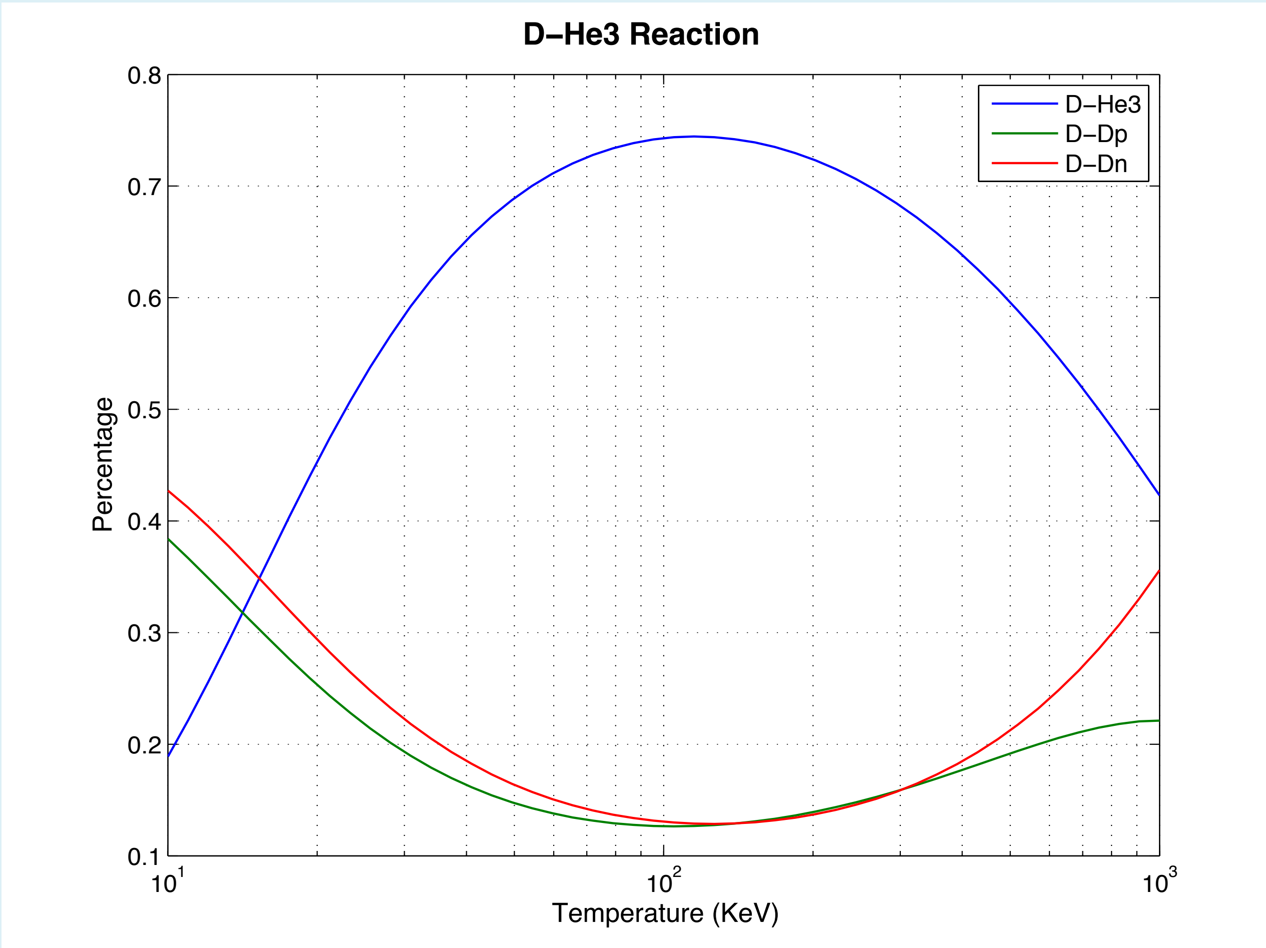
Introduction

- Aneutronic Fusion
- Fusion Engine Concepts
- Mission Plan
- The Modular Aneutronic Fusion Engine
- Starship Design
- Summary and Conclusions

Aneutronic Fusion

- Fusion reactions that produce few neutrons
  - $D + {}^3He \rightarrow {}^4He\ (3.6\ MeV) + p\ (14.7\ MeV)$
    - Plus significant side reactions
      - $D + D \rightarrow 2T\ (1.01\ MeV) + H\ (3.02\ MeV)$
      - $D + D \rightarrow 2\ {}^3He\ (0.82\ MeV) + n\ (2.45\ MeV)$
  - $p + {}^{11}B \rightarrow 3\ {}^4He + 8.6\ MeV$
- Fusion products can be exhausted directly through a magnetic nozzle to produce thrust
  - Jet exhaust is somewhat more complicated with spherical or toroidal geometries
- These reactions require much higher plasma temperatures than D-T

D-^{3}He Side Reactions



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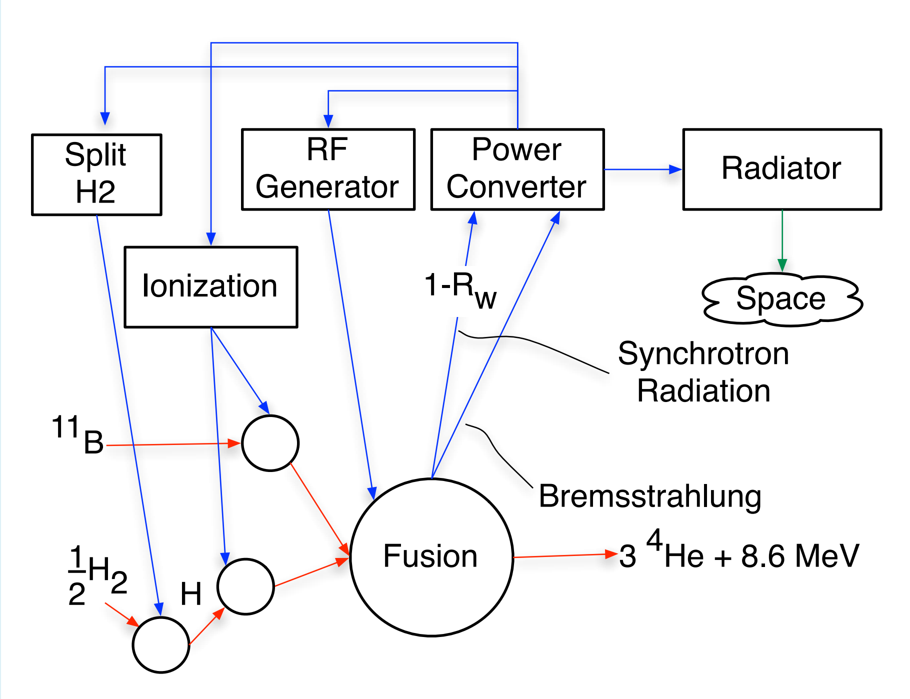
Fuel Sources

- Boron-proton
  - Boron is readily available
- Deuterium-Helium 3
  - ^{3}He is very rare
  - Volcanoes
  - Bombardment of lithium produces tritium which decays
  - Lunar mining

The Fusion Energy Balance

- p+^{11}B reaction in this case
- Bremsstrahlung due to electron braking – worse at high temperatures
- Synchrotron is RF – worse at high temperatures and high magnetic fields
- Can recycle some of the losses via a heat engine
- Ideal D-He3 reaction
  - Cold electrons
  - Hot ^{3}He
  - D in the middle

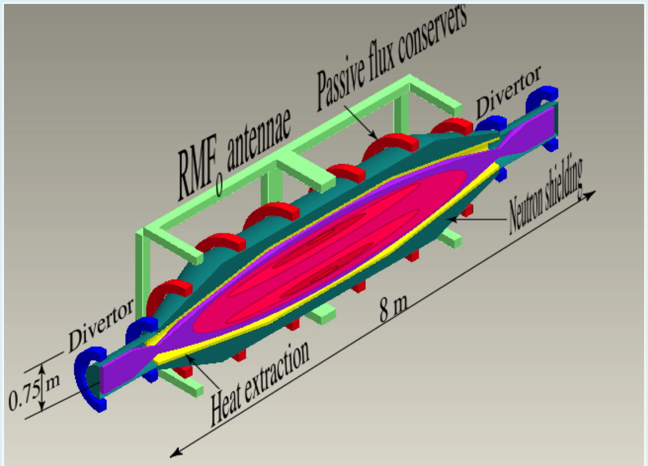


Fusion Engine Concepts

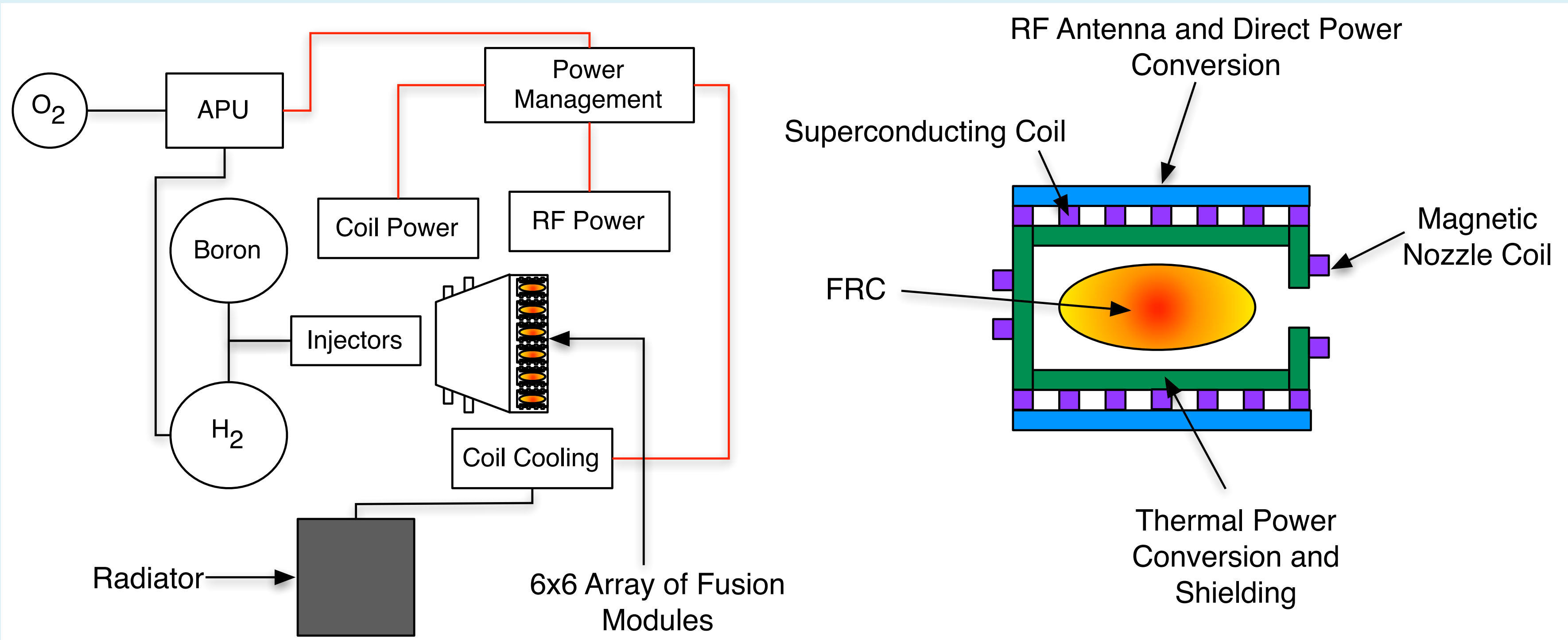
- Many engine concepts have been investigated
  - Levitated dipole
  - Spherical tokamak with poloidal divertor
  - Gas dynamic mirror
  - Magnetic target fusion with plasma beams
  - Pulsed high density fusion rocket
  - Spherical tokamak with ripple effects for thrust extraction
  - Colliding beam FRC
  - RF heated FRC (our concept)
  - Many others
- Many of these are candidates for terrestrial power generation

Fusion Engine 1/4

- Key Elements: FRC, RF heating and magnetic nozzle
  - Makes a small, 5 – 10 MW fusion reactor feasible
  - Cigar shaped reactor – elongation improves stability and produces more power
- Fuel
  - D-^{3}He maintain pressure by having a ratio of 1 D to 2 ^{3}He while reducing D-D side reactions
- Field Reversed Configuration
  - Elongated plasma ellipsoid in which an azimuthal current reverses the field
  - Ratio of magnetic pressure to plasma pressure nearly 1 – only levitated dipole is better
  - Can use passive flux conservers – strips of high temperature superconducting film eliminates the need for active superconductors for confinement
- Radio Frequency Heating
  - Odd parity rotating magnetic field – heats electrons
  - Electrons transfer power to ions
  - Get explosive heating of ions
  - Physics of RF interaction with dense plasmas not well understood



Fusion Engine 2/4



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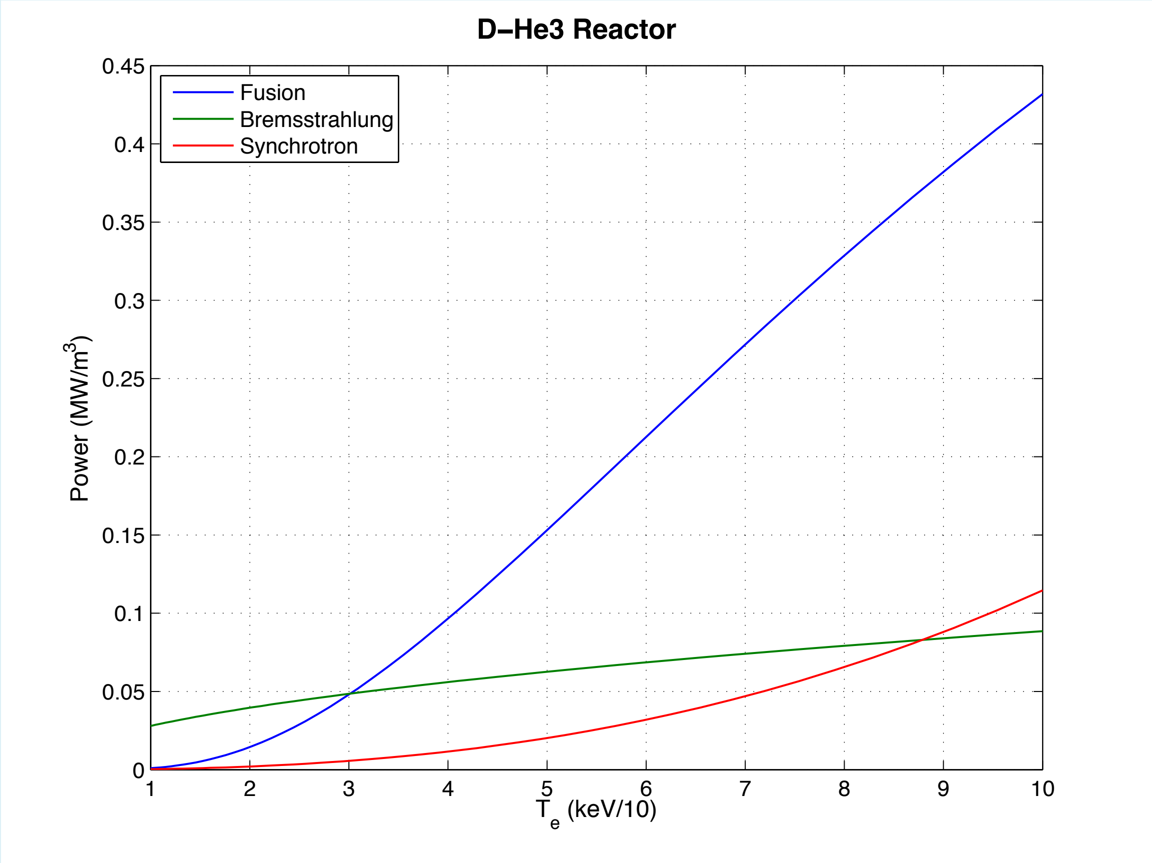
Fusion Engine 3/4

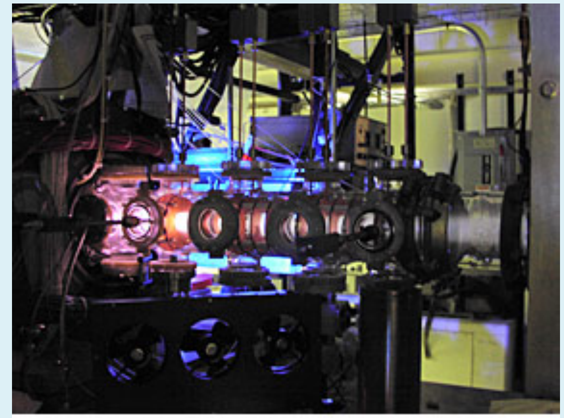


Fusion Engine 4/4

Parameter	Value
Fuel	1.0 D^3He
First Wall Thermal Power (MW/ m^2)	0.3
Aspect Ratio (L/R)	15.00
Plasma Radius (m)	0.36
Plasma Volume (m^3)	2.18
RMS Plasma Pressure (Pa)	5.2e+06
Central Plasma Pressure (Pa)	1.0e+07
Average Magnetic Field at Coil (T)	3.6
Shield EM Attenuation	1.00e-07
Magnet Mass (kg)	7.29e+01
Shield Mass (kg)	4.19e+03
Power Conversion Mass (kg)	8.21e+03
Radiator Mass (kg)	2.04e+03
Total Mass (kg)	1.45e+04
Specific Mass (kW/kg)	0.69
Central Temperature (keV)	100
Deuterium Density (10^{20} m^3)	1.3
Helium-3 Density ($10^{20}/m^3$)	1.3
Electron Density ($10^{20}/m^3$)	3.9
Synchrotron (MW/m^3)	0.10
Bremsstrahlung (MW/m^3)	1.89
Confined Gyro Radii	46.4
Fusion Power (MW)	14.3
Net Power (MW)	10.0

Ongoing Research at PPPL

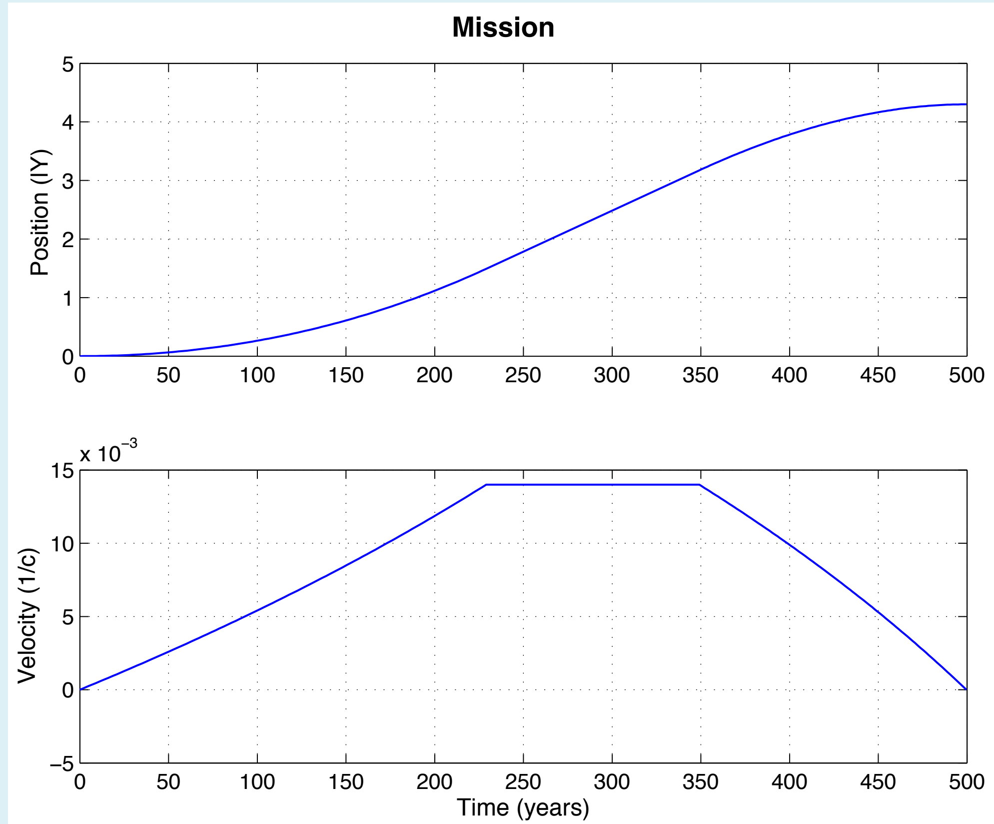
- Magnetic nozzle experiment (MNX)
  - Studying recombination and phase transition
- FRC
  - Investigating non-ideal MHD effects
  - FRC stability properties
  - Complete understanding of FRC stability is lacking
  - RF heating for dense plasmas



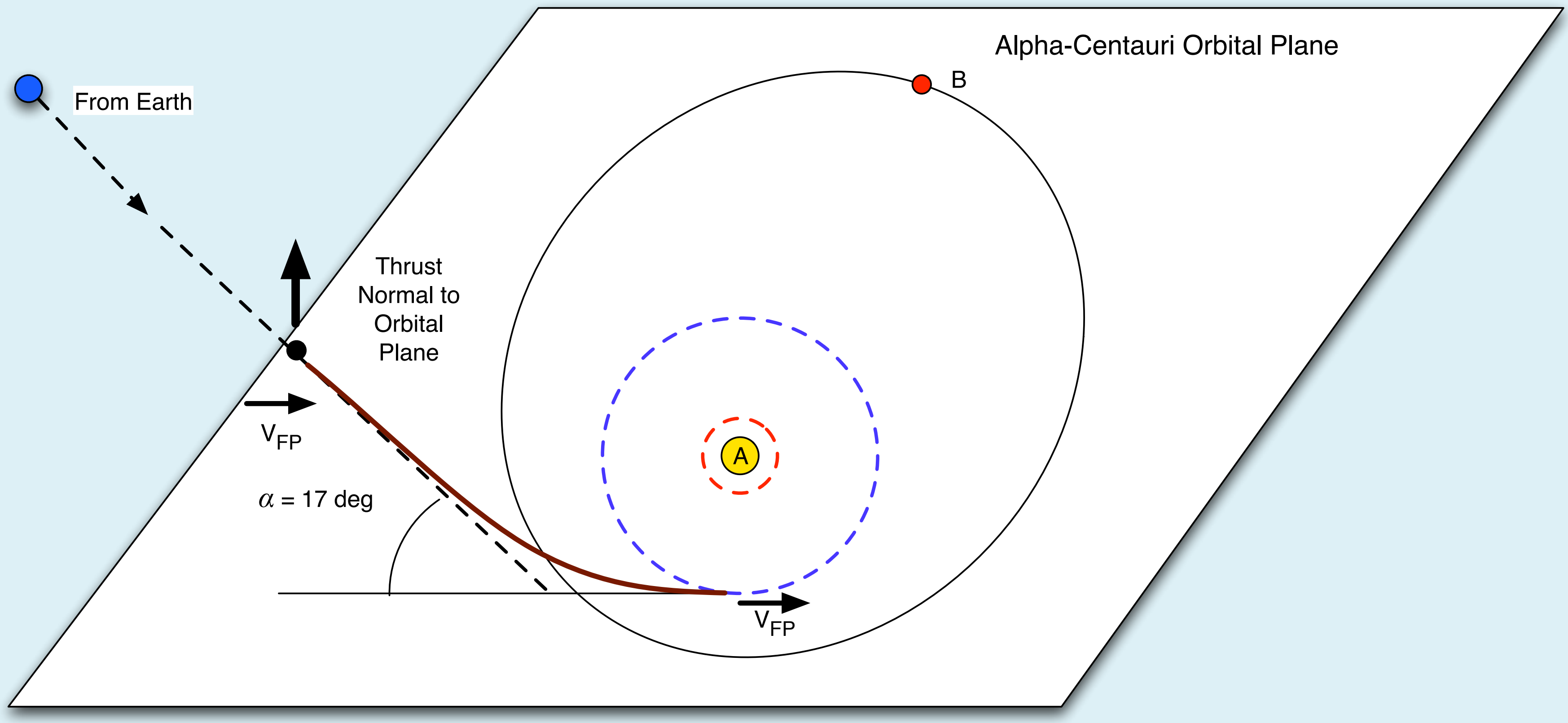
MNX — Magnetic Nozzle Experiment

Mission Design 1/3

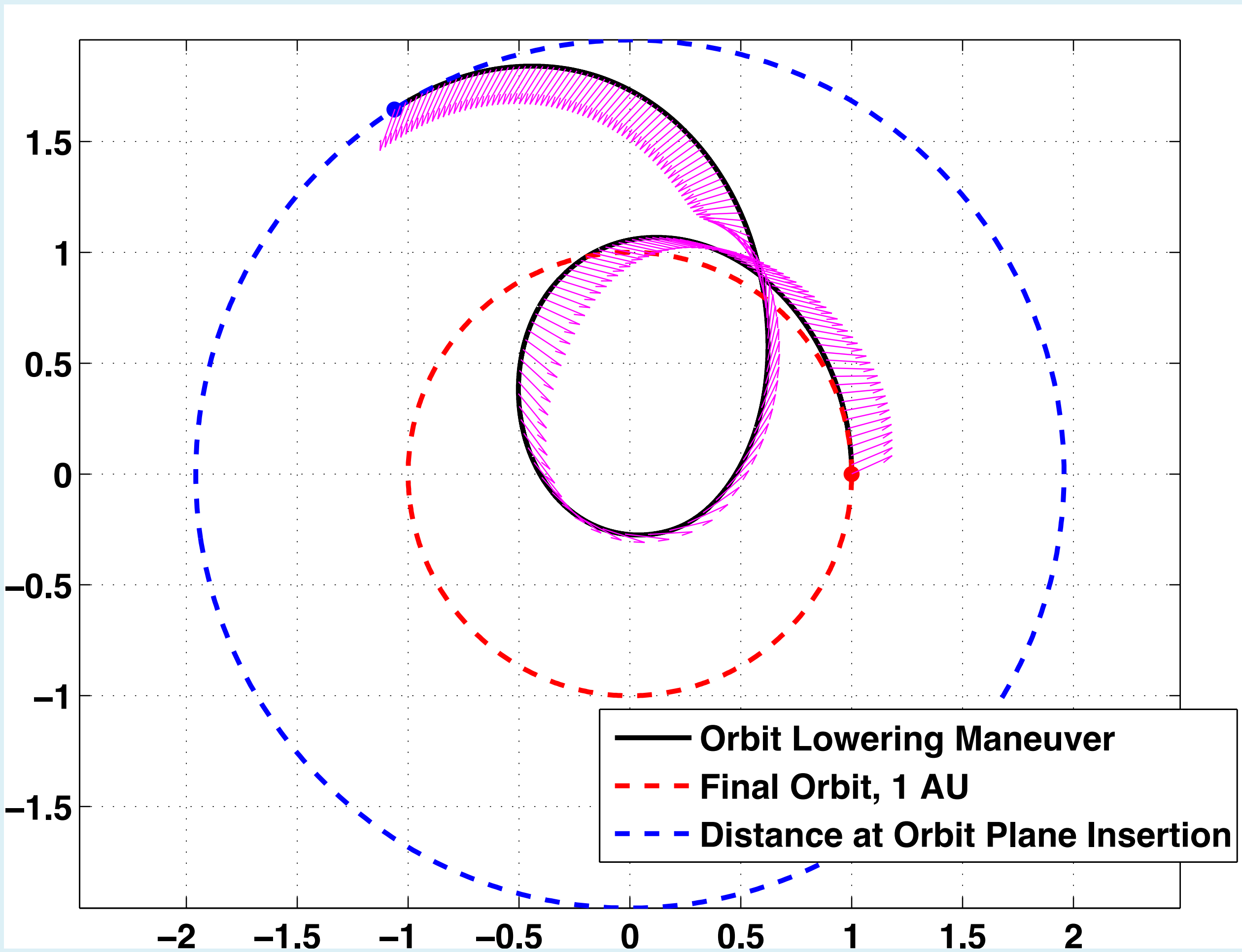
- Orbiting crewed assembly station in polar orbit
- Starship assembled and tested
  - 16 launches of Falcon 9 Heavy
  - Fewer with NASA HLV
- Departure using a liquid booster stage
- 14 N constant thrust
  - Not necessarily optimal thrust
- Exhaust ½ maximum from D-^{3}He
  - Not necessarily the optimal exhaust velocity
- Assumes 10 kW/kg
  - Our work shows 670 W/kg!
- Arrives at Alpha-Centauri in 500 years
- Goes into 1 AU orbit around A or B
- Then goes into polar orbit around planet



Mission Design 2/3



Mission Design 3/3



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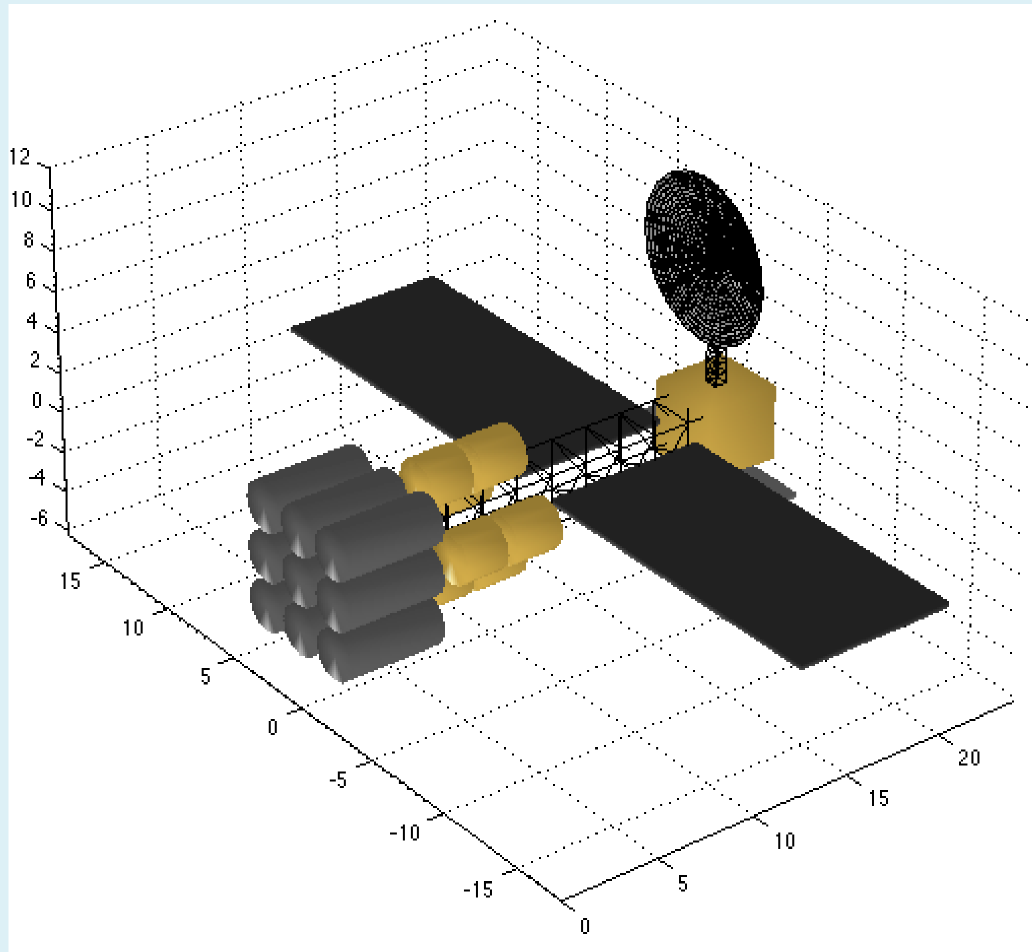
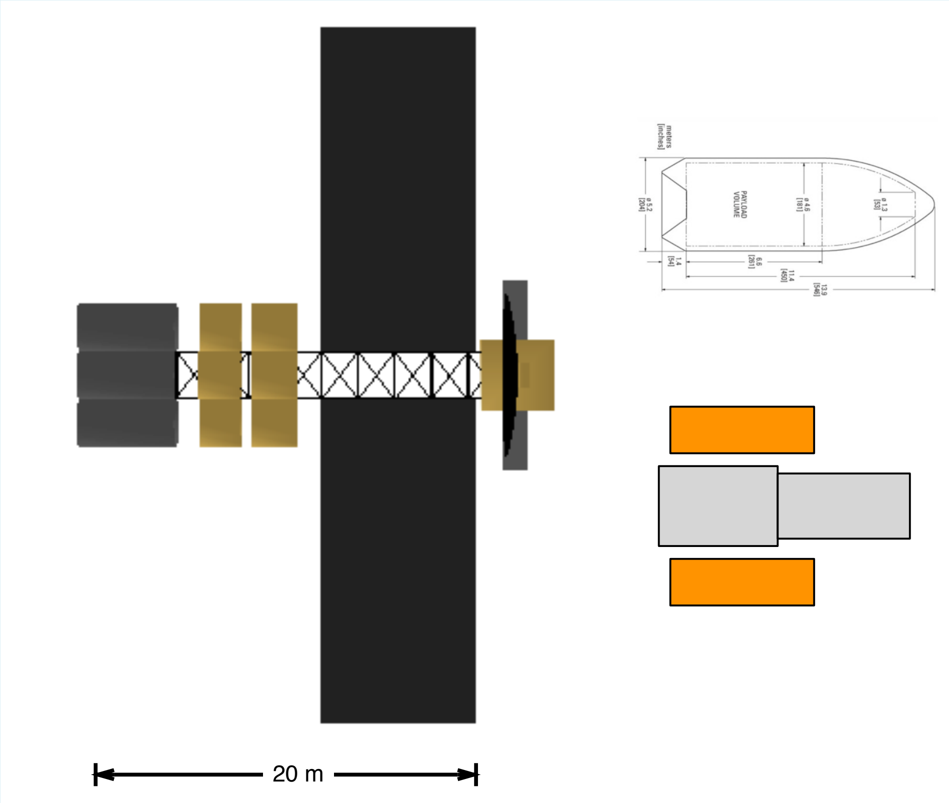
Starship Conceptual Design 1/2

- Nine 10 MW engines
- 16 m antenna
- 0.5 m aperture telescope for navigation and science
- Communications 1 kpbs
- Pointing control differential thrust and CMGs



Starship Conceptual Design 2/2

Shows Falcon 9 Heavy shroud and Hubble Space telescope



Lifetime

- 500 years to reach Alpha-Centauri
- Neutron bombardment the major limitation to engine life
  - Boron proton 1000 times lower neutron flux than deuterium helium-3
  - Reduce neutron flux by choice of temperature and using less D in the reactor
- Longest lived satellites are Voyager 1 and 2 – 34 years
- Comsats routinely reach 15 years – fuel is the major life limiting factor

Summary and Conclusions

- Fusion propulsion enables interstellar missions
- A mission to Alpha-Centauri is feasible assuming that a fusion engine can be built
- Improvement of specific power critical
  - Magnetized target fusion claims 400 kW/kg!
- Neutron damage a major issue for the engines
  - Boron proton reaction would reduce this drastically
- Significant science and engineering required
  - Liquid rockets were demonstrated by Goddard in 1923
  - Fusion breakeven has not yet been demonstrated
- Modular Fusion Engine permits Robert Goddard like program because of its size
  - Build a test model then build another – huge budgets not required

Future Work

- Continue development of the RF heated FRC
  - Successful reactor would also help solve terrestrial energy problems
- Development of engine optimization tools
  - Find the optimal densities and temperatures
  - Heat engine optimization
  - 3D plasma models
- Trajectory optimization
  - Variable thrust and exhaust velocity
  - Star system arrival guidance

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