Direct Fusion Drive

provide game-changing power and propulsion in space

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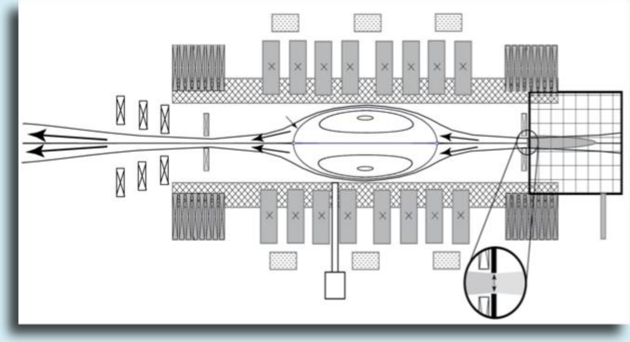
Talk Outline

- PFRC Reactor Design and Experiments
- Variable Thrust and Specific Impulse via Augmentation
- Missions
  - Alpha Centauri
  - L2 Space Telescope
  - Asteroid Deflection
  - Mars Mission
- Conclusions

Summary

- **DFD produces power AND thrust**
- FRC fusion reactor exhausts fusion products plus additional deuterium to produce thrust
- Heating method naturally limits size: 1-10 MW and size of minivan
- Low neutron radiation using ^{3}He as fuel
  - ^{3}He is in limited supply, enough for approx. 100 MW/year
- Perfect for space applications



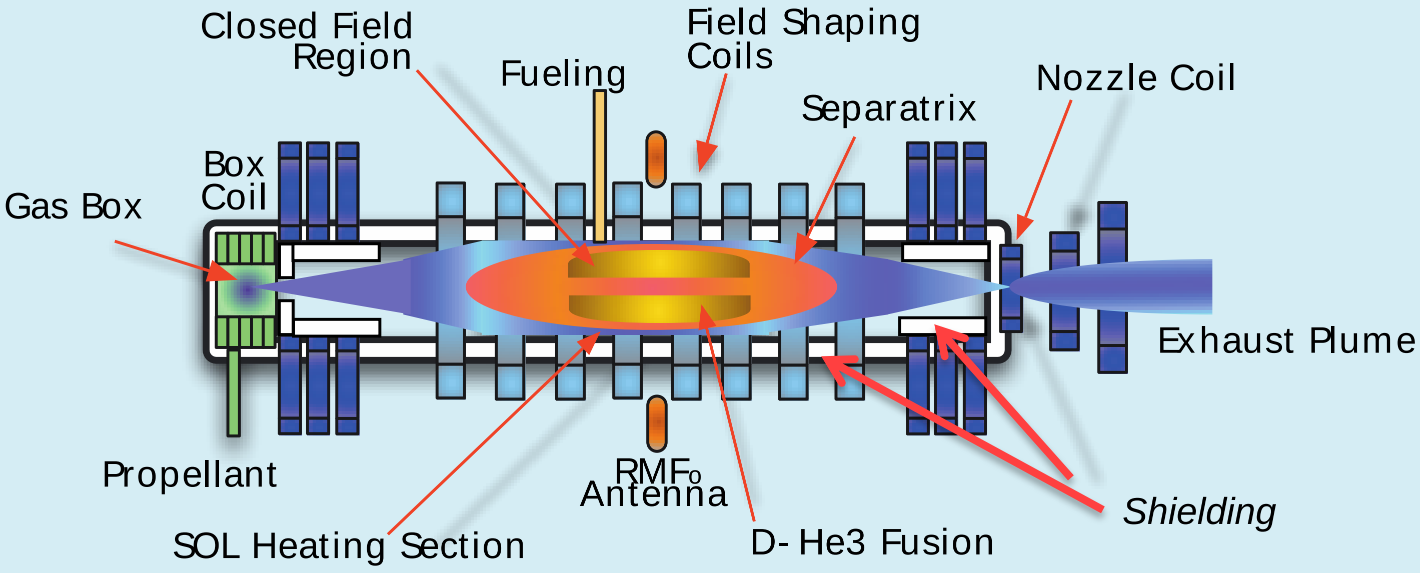
PRFC Reactor Design

UNIQUE PRFC DESIGN

Princeton Field Reversed Configuration (PFRC)

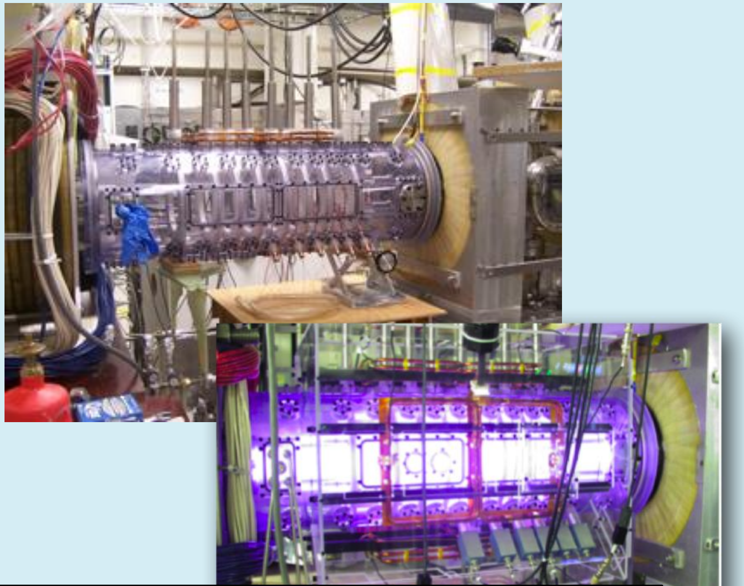
- Field Reversed Configuration (FRC)
  - Simple geometry with fewer coils
- RF heating with odd-parity rotating magnetic fields naturally limits reactor size
  - Plasma radius in range 20-40 cm
  - Size of 1-10 MW which is ideal for space
- Confinement with high temperature superconducting coils
- Burns aneutronic D and ^{3}He with beta greater than 0.8

- Linear configuration allows for configuration as a rocket engine
- Magnetic Nozzle
- Add H or D^+ to augment thrust
- Variable exhaust velocity
  - 50 to 20,000 km/s
  - $P = 0.5\ Tu_E/\eta$, with $\eta \sim 0.5$



PFRC Experiments at PPPL

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

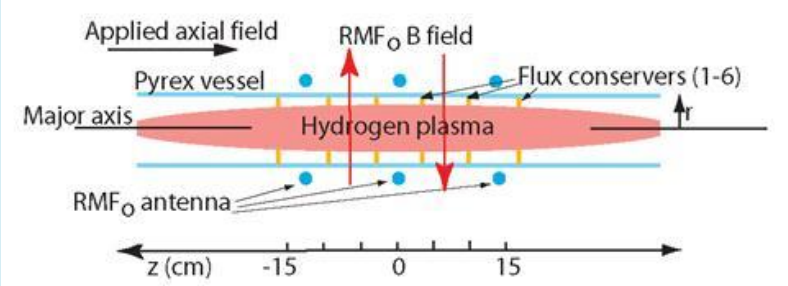


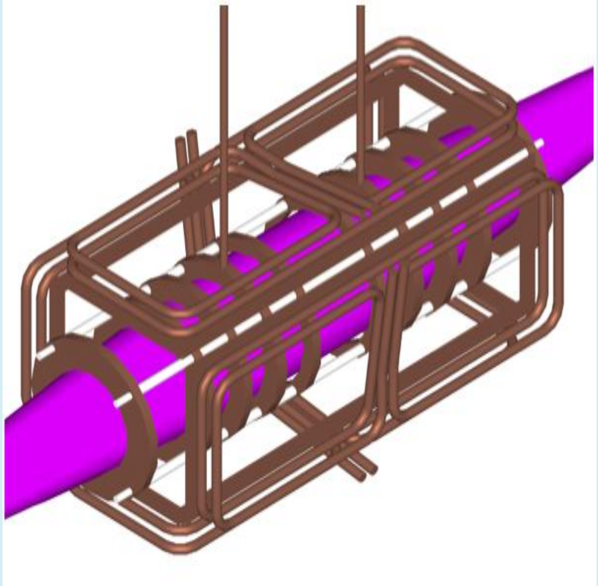
Machine	PFRC-1	PFRC-2	PFRC-3	PFRC-4
Objectives	Electron Heating	Ion Heating	Heating above 5 keV	D-He3 Fusion
Goals/ Achievements*	3 ms pulse* 0.15 kG field* e-temp = 0.3 keV*	0.1 s pulse* 1.2 kG field i-temp = 1 keV	10 s pulse 10 kG field i-temp = 5 keV	1000 s pulse 60 kG field i-temp = 50 keV
Plasma Radius	4 cm	8 cm	16 cm	25 cm
Time Frame	2008-2011	2011-2015	2015-2019	2019-2023
Total Cost	$2M	$6M	$20M	$50M

Rotating Magnetic Fields (RMF)

- Parity refers to the symmetry of the magnetic field mirrored across the z=0 midplane
- Frequency is a fraction of the ion cyclotron frequency for the helium-3
  - Would be 0.3 to 2 MHz
- Provides all the startup power and a fraction of the heating power during operation
- RF antennas shown to the right

PFRC-2 Design



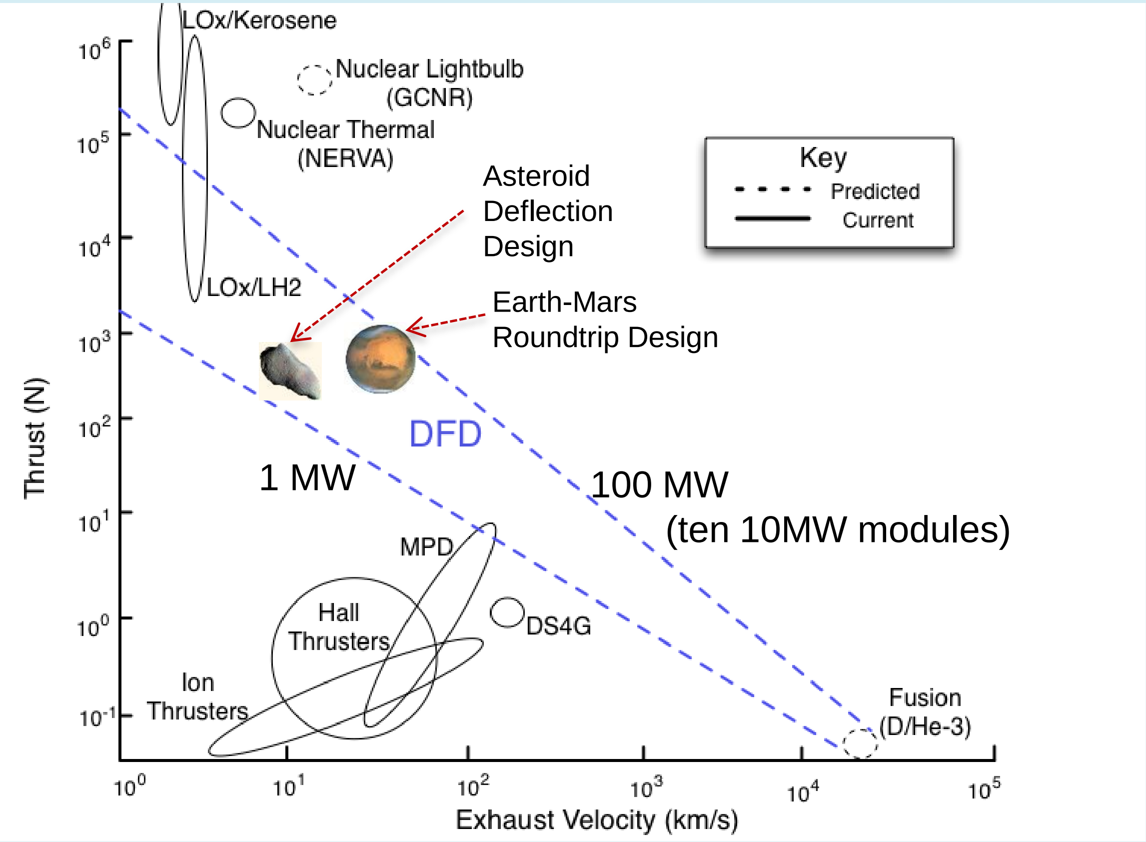


RMF$_o$ Antennas

Variable Thrust and Isp

THRUST AUGMENTATION WITH D$^+$

DFD Thrust and Isp Envelope



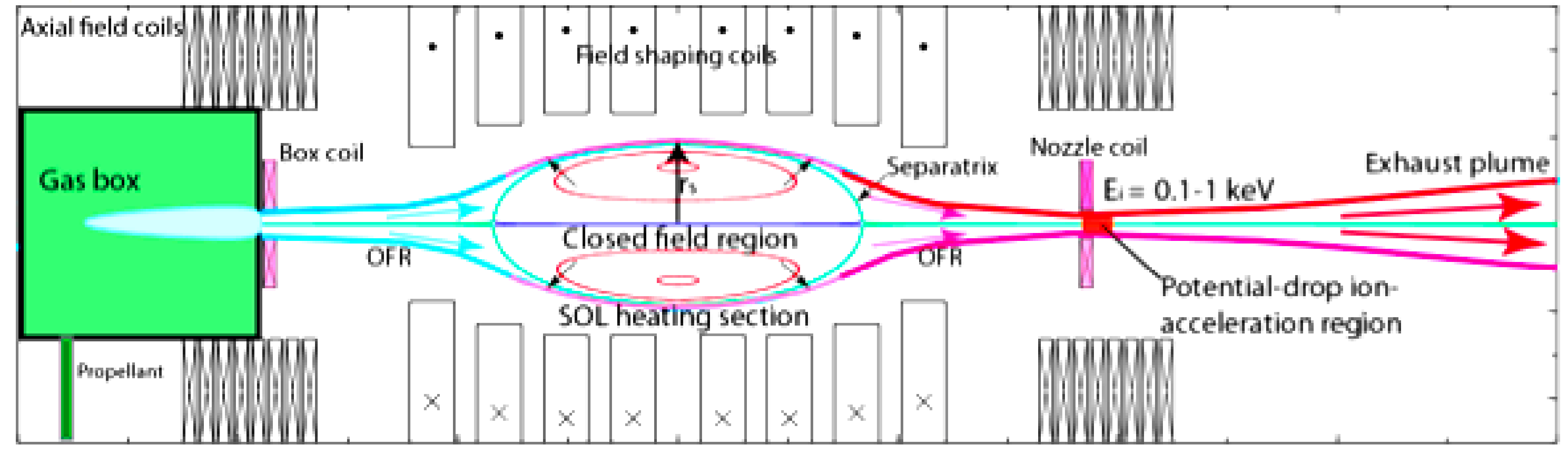
$$P = \frac{1}{2}\frac{T u_e}{\eta}$$

$$\dot{m} = T/u_E$$

- The DFD design envelope fits between traditional chemical, electric and nuclear propulsion methods.
- Fusion products of the deuterium-helium-3 (D/He^3) reaction have a very high exhaust velocity: 25,000 km/s
- We can convert some of their kinetic energy into thrust by transfering evergy from the fusion products.

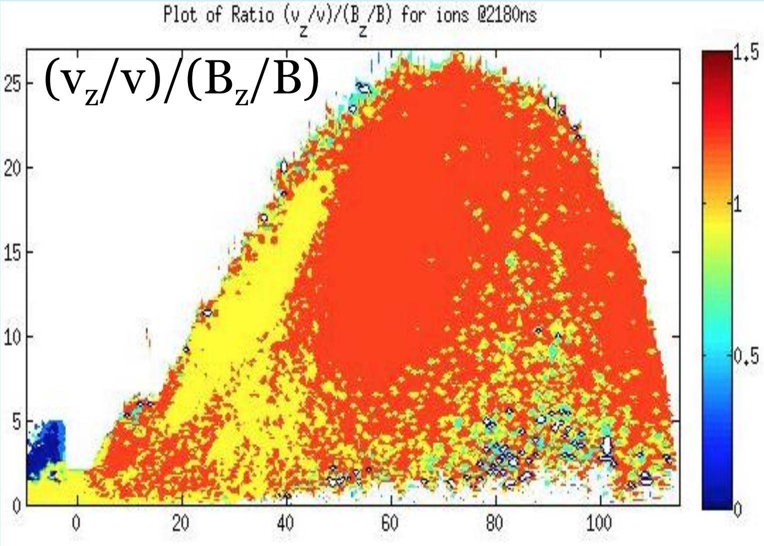
Thrust Augmentation

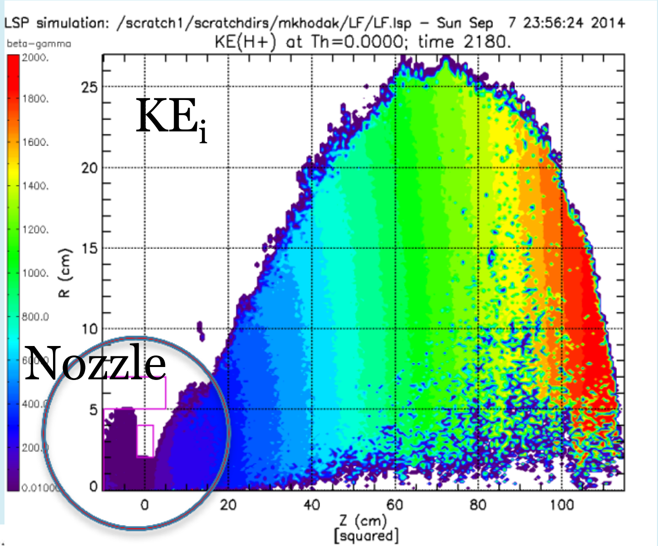
- H or D is used as a **propellant**- it flows along the magnetic field lines outside of the separatrix; scrape-off layer (SOL) e- are heated by the fusion products that are ejected into the SOL; e- energy transferred to ions in plume expansion
- This reduces the exhaust velocity of the fusion products from 25,000 km/s to ~50 km/s and increases thrust to >20 N
- Thrust/Isp 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.

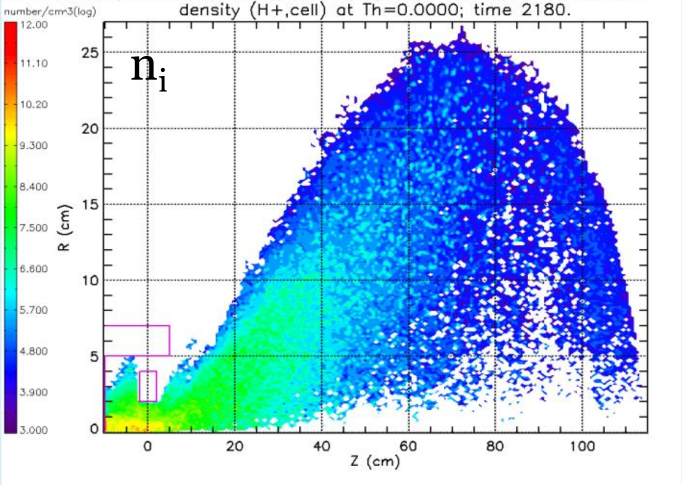


Magnetic nozzle: 3D simulations in LSP

Modeling provides evidence for detachment







Expanding plasma plume at 2.18 μs

Inside nozzle:

$n_e = 10^{11}$ cm^{-3}

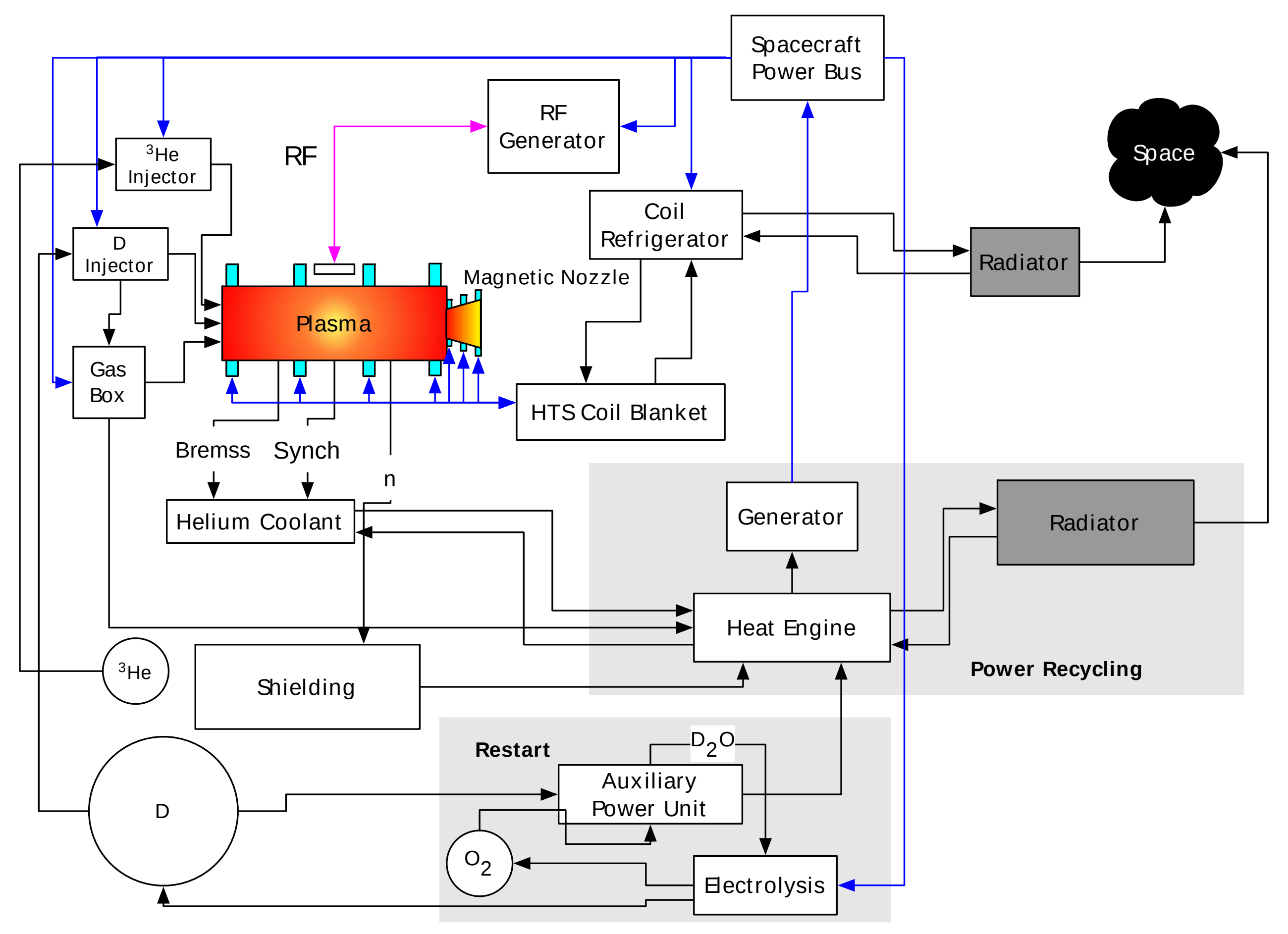
$T_i = 1$ eV

$T_e = 100$ eV

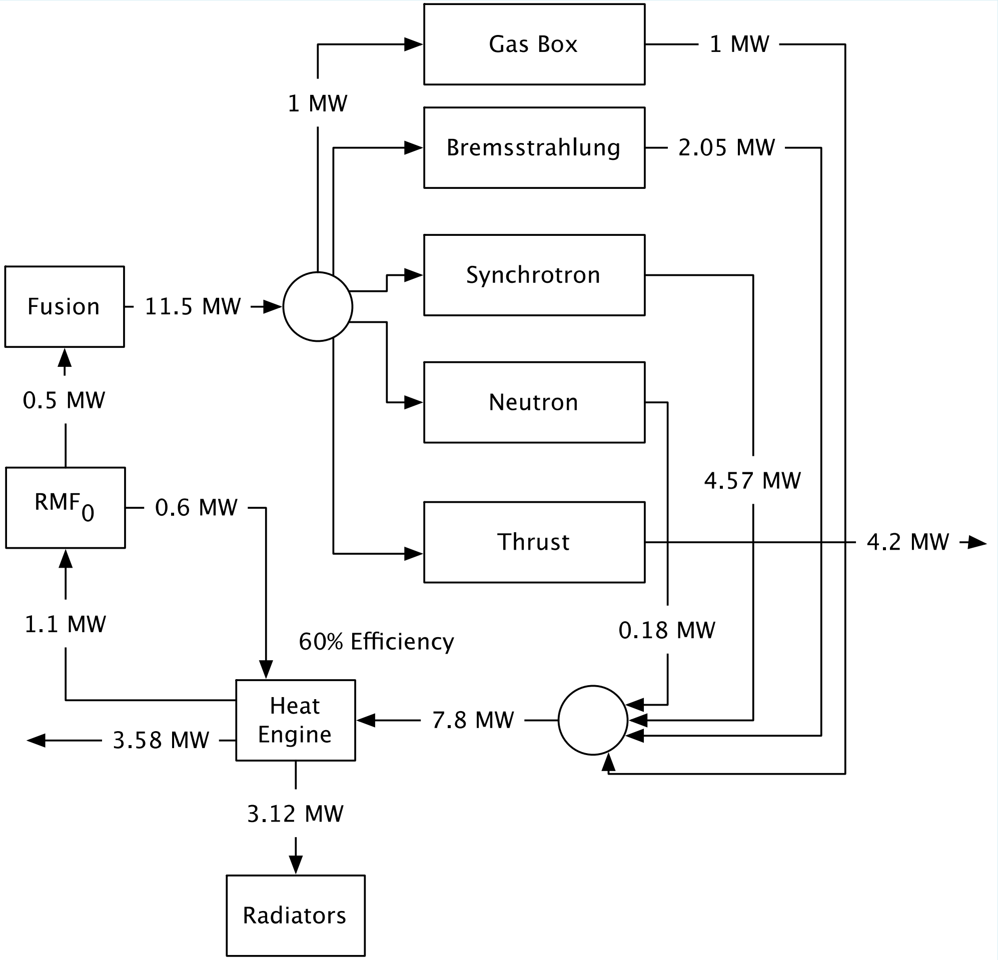
At z = 100 cm:

KE (H^+) ~ 2 keV

Space Plant Components



Mars Mission Energy Balance



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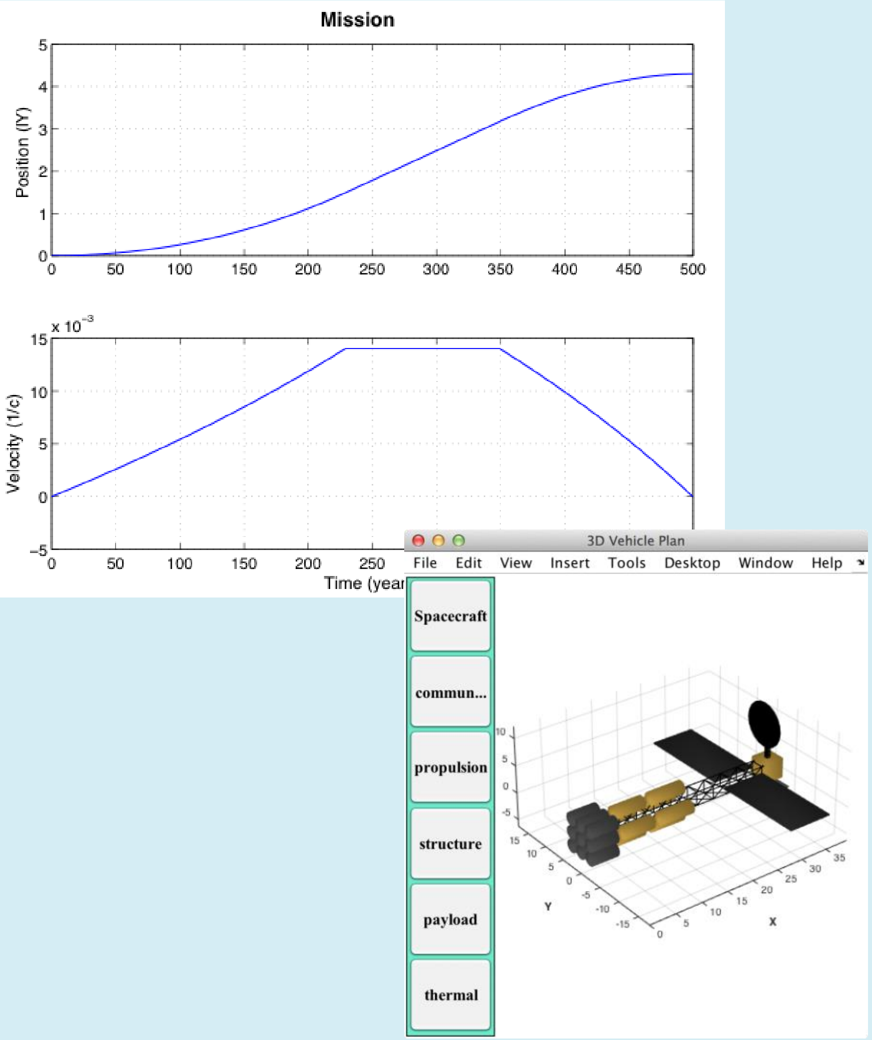
Alpha Centauri Starship

VISIT THE STARS!
DARPA 100 YEAR STARSHIP SYMPOSIUM
2011

Synopsis: Alpha Centauri

- Stable orbits possible around stars A and B
- Deliver 500 kg payload
- Nine 10 MW engines
    - 14 N thrust
    - u_E 12,000 km/s
    - 500 year transit
    - Achieve 0.15 c
- Two 10 MW engines
    - 7.5 N thrust
    - u_E 3200 km/s
    - 700 year transit
    - 3He 564.7 kg



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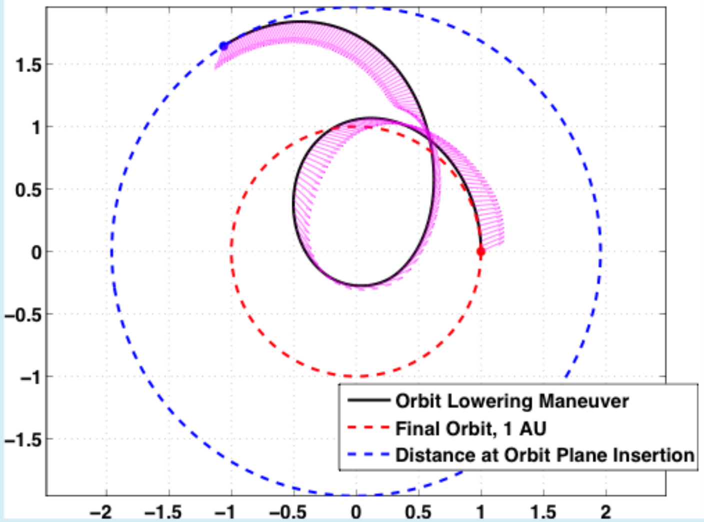
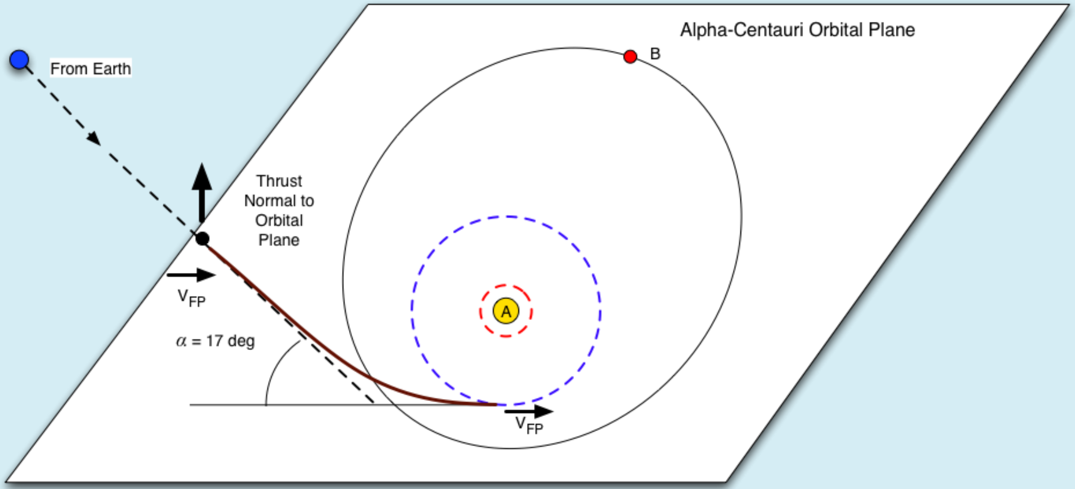
Final Orbit Insertion

- Go into 1 AU orbit around star A or B
- Then transfer into polar orbit around (potential) planet





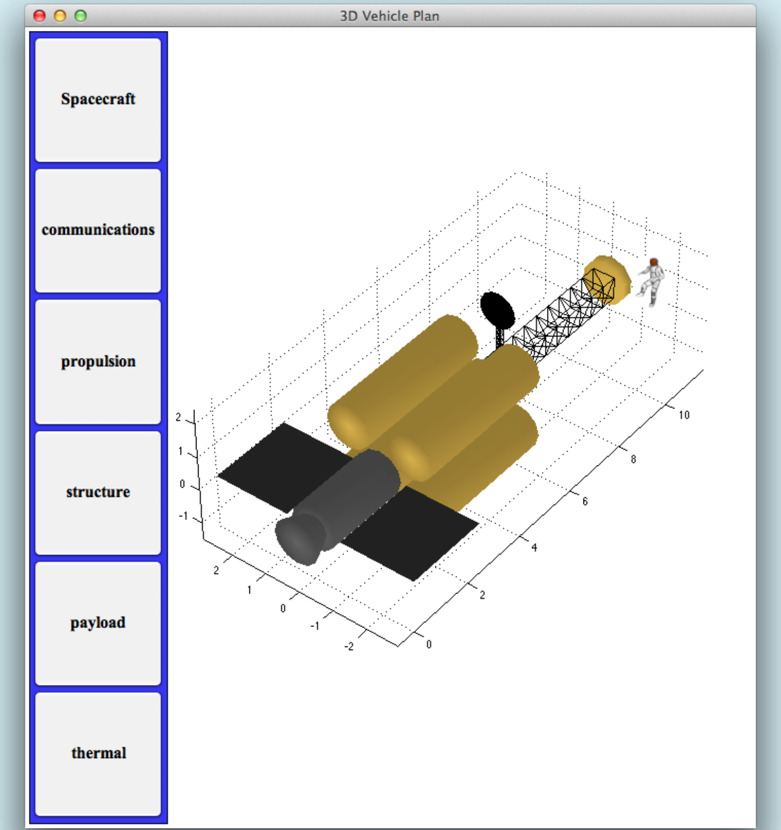
L2 Space Telescope

INTERPLANETARY SPACE TUG

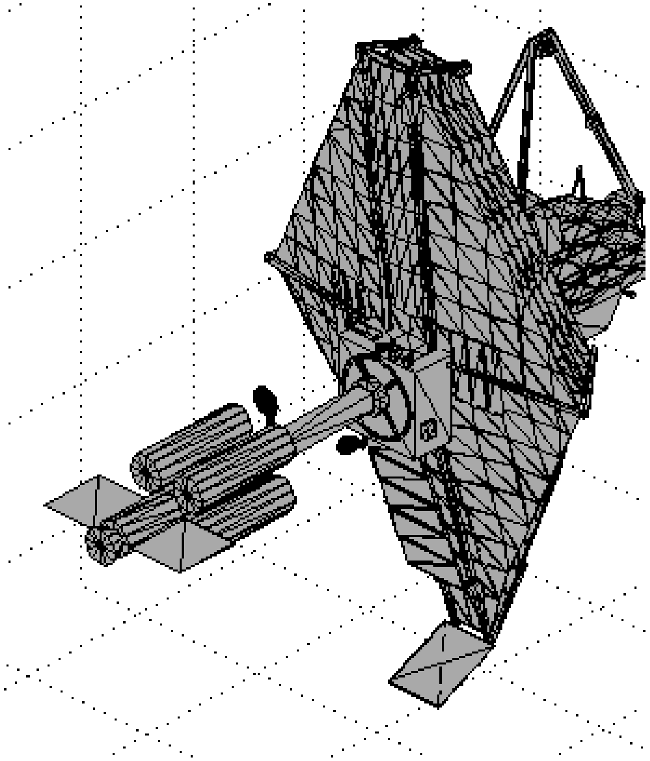
IAC 2012

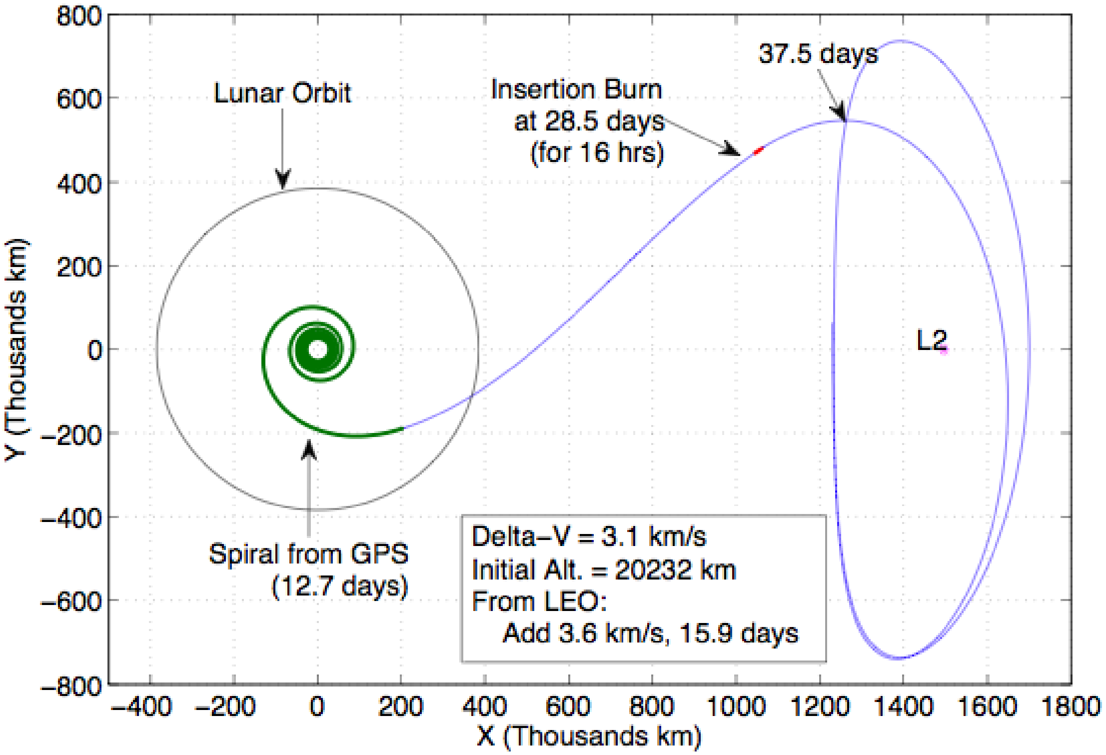
Mission: Telescope to Sun-Earth L2

- 1 MW engine
  - Electrical power 1.25 MW
  - Propulsion power 1.13 MW
- Transit ~40 days from GPS
- Payload mass 6200 kg
- ΔV 3.1 km/s
- 40 N thrust
- u_E 56.5 km/s
- 3He 50 g
- D 353 kg



Deploying the James Webb Telescope





Circular restricted three-body simulation

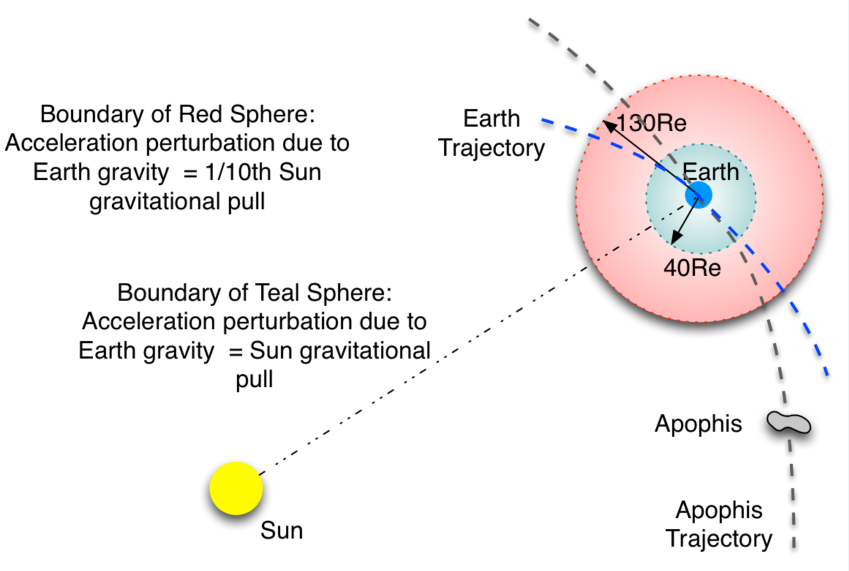
Asteroid Deflection

SAVE THE WORLD!

IEPC 2013

Synopsis: Asteroid Deflection

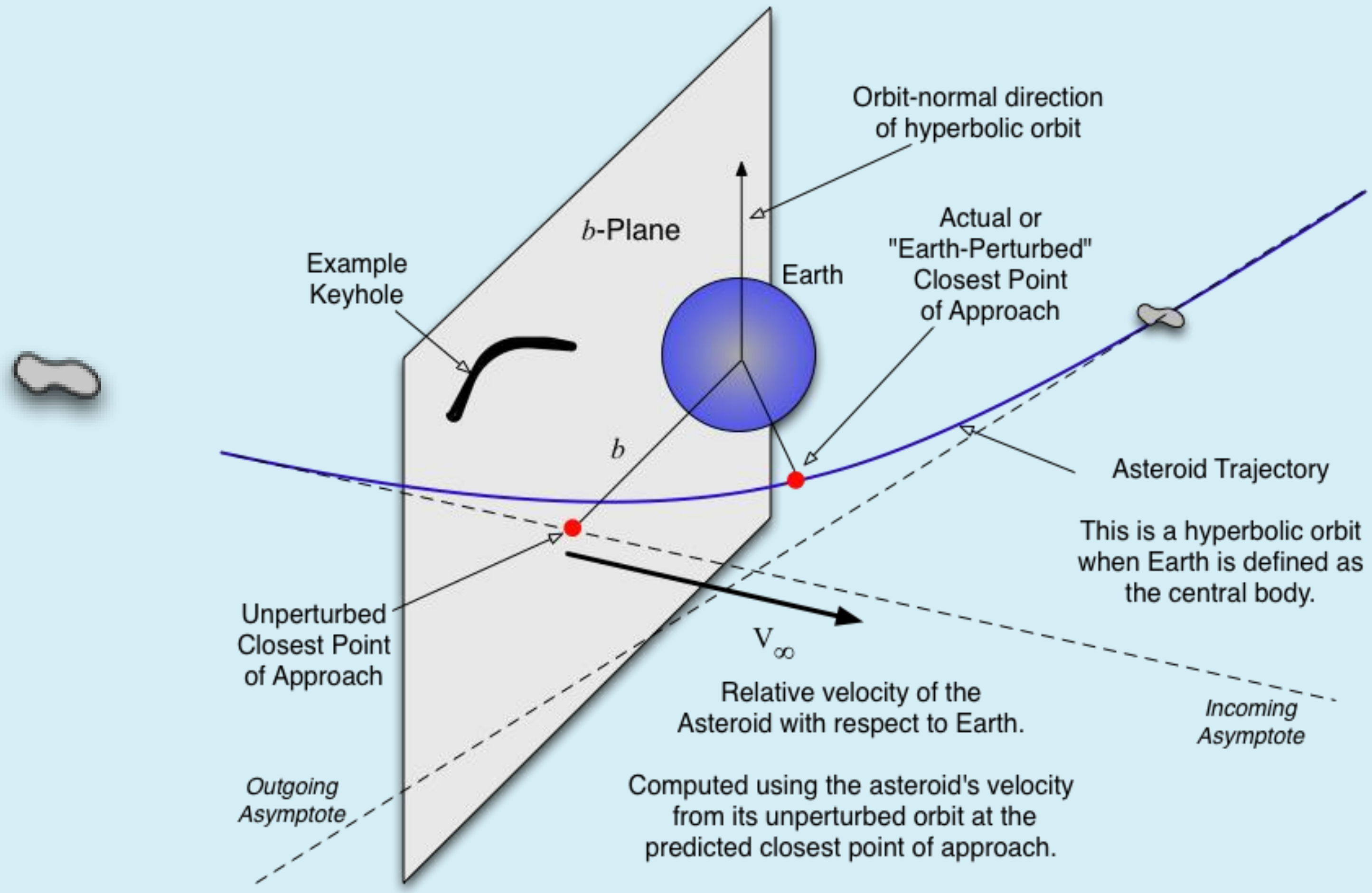
- Must reach an asteroid and apply DV to it to avoid orbital keyhole
- ΔV to Apophis 10-30 km/s in 175-270 days
- ΔV to asteroid 0.3 m/s
- 10 MW engine
- Thrust: 500 N
- Burn time: 23 days
- Mass flow 0.02 kg/s
    - 41000 kg propellant



Boundary of Red Sphere: Acceleration perturbation due to Earth gravity = 1/10th Sun gravitational pull

Boundary of Teal Sphere: Acceleration perturbation due to Earth gravity = Sun gravitational pull

Asteroid Deflection Maneuvers



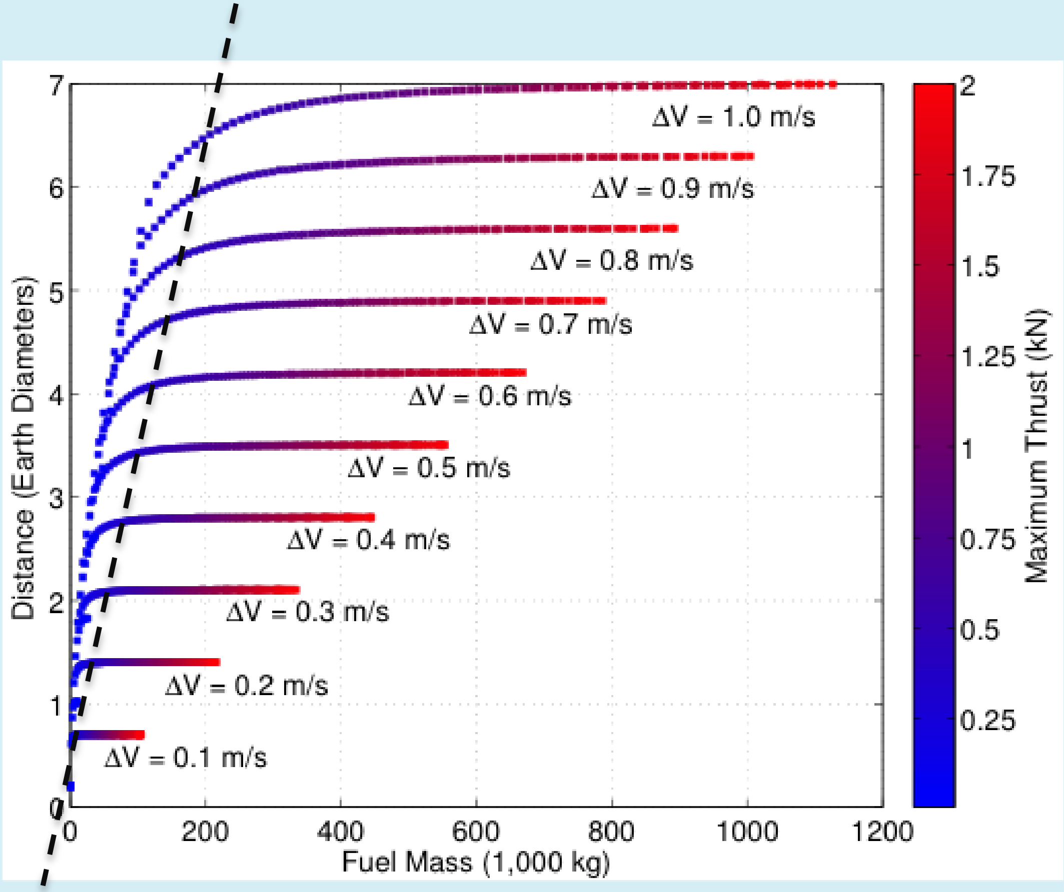
This is a hyperbolic orbit when Earth is defined as the central body.

Relative velocity of the Asteroid with respect to Earth.

Computed using the asteroid's velocity from its unperturbed orbit at the predicted closest point of approach.

Deflection Capability Analysis

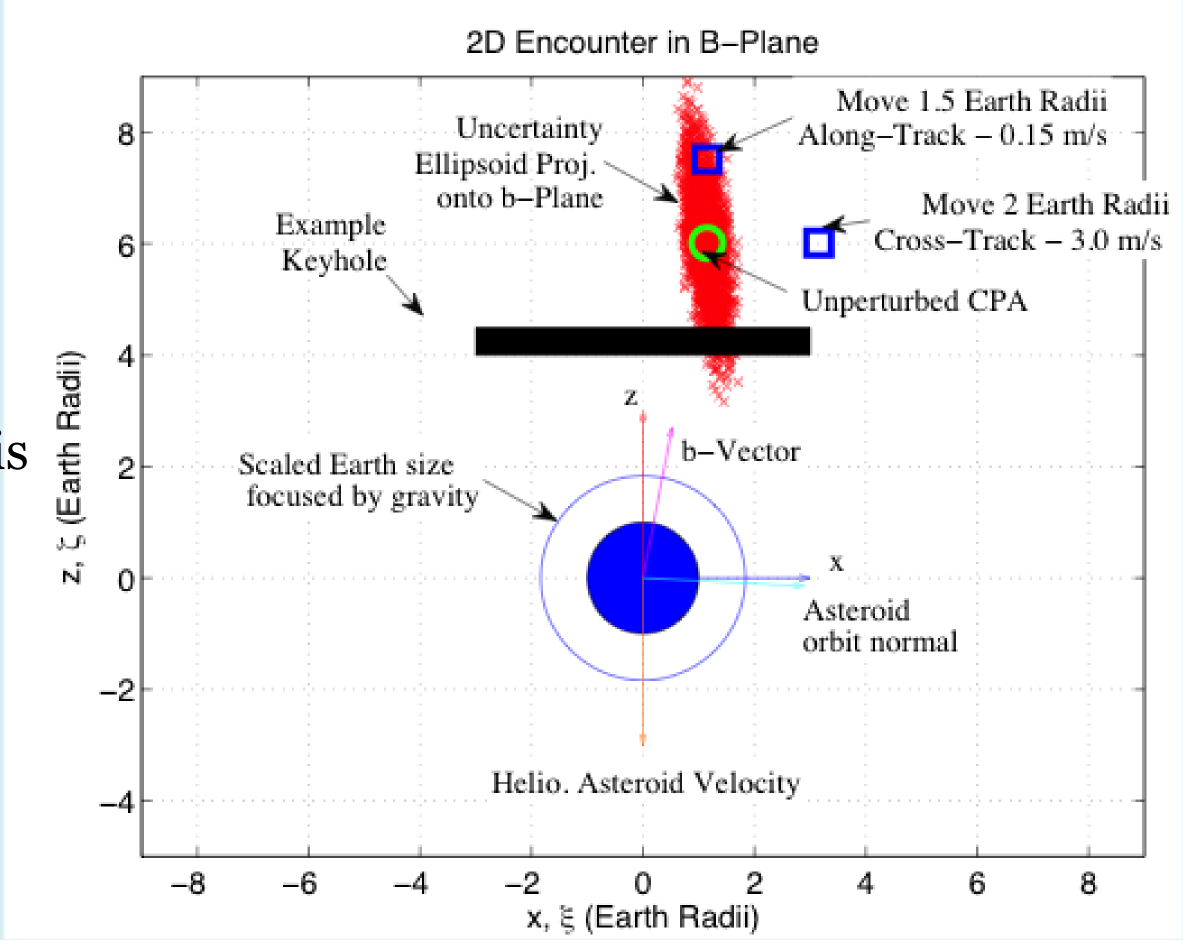
- Use Apophis 2029 encounter with Earth
  - Consider an asteroid half the size of Apophis
- Maxmize separation at time of impact
  - Maximize distance
  - Vary delta-v
  - Vary thrust level
- Investigate tradeoff of deflection distance vs. fuel mass



"Knee" at 500 N

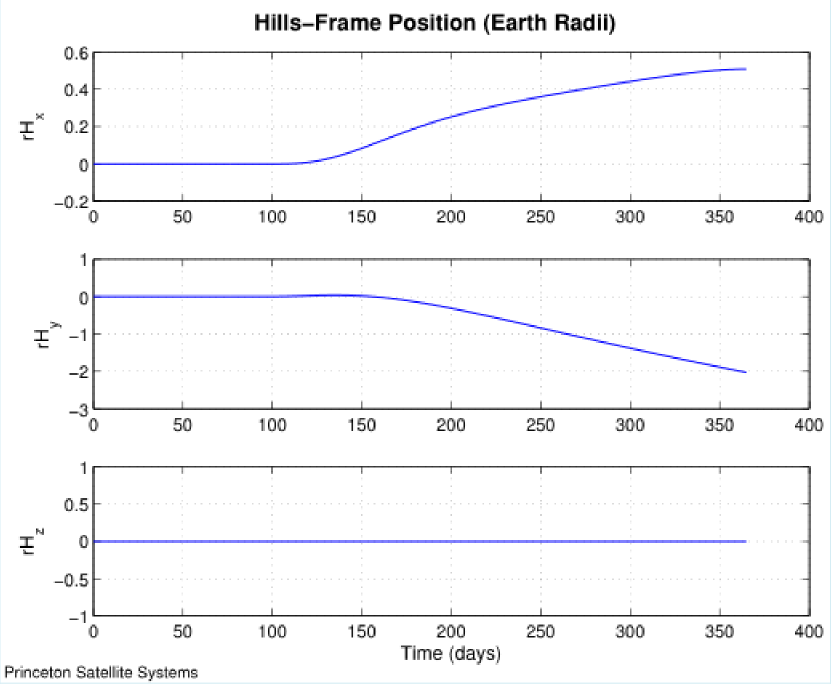
Example Deflection Geometry

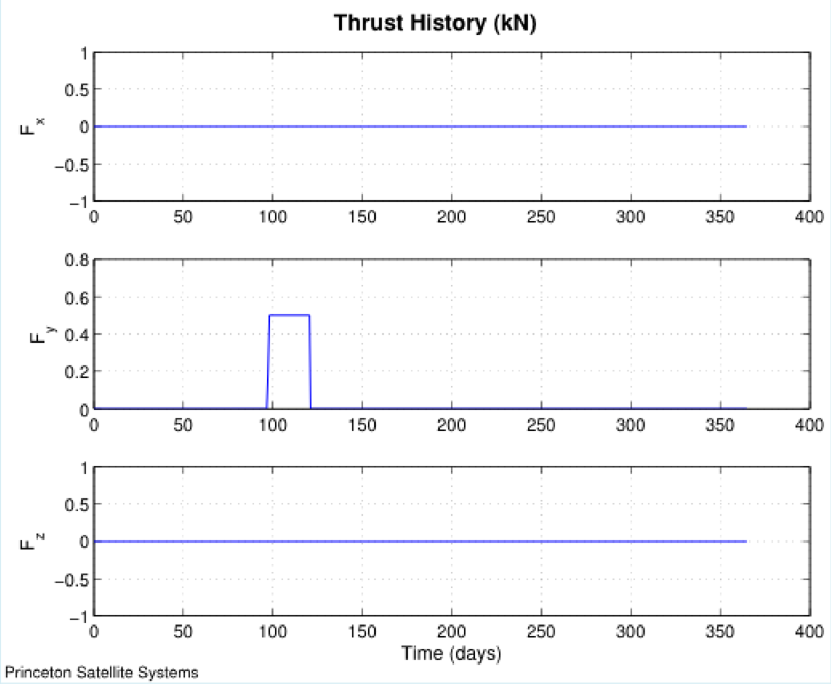
- Consider two maneuvers
  - Along-Track (vertical)
  - Cross-Track (horizontal)
- Goal is to move ellipse away from keyhole and Earth focus
- Along-track deflection is always much easier



Example Deflection Maneuver

- Maximizing deflection distance (with ΔV limit)

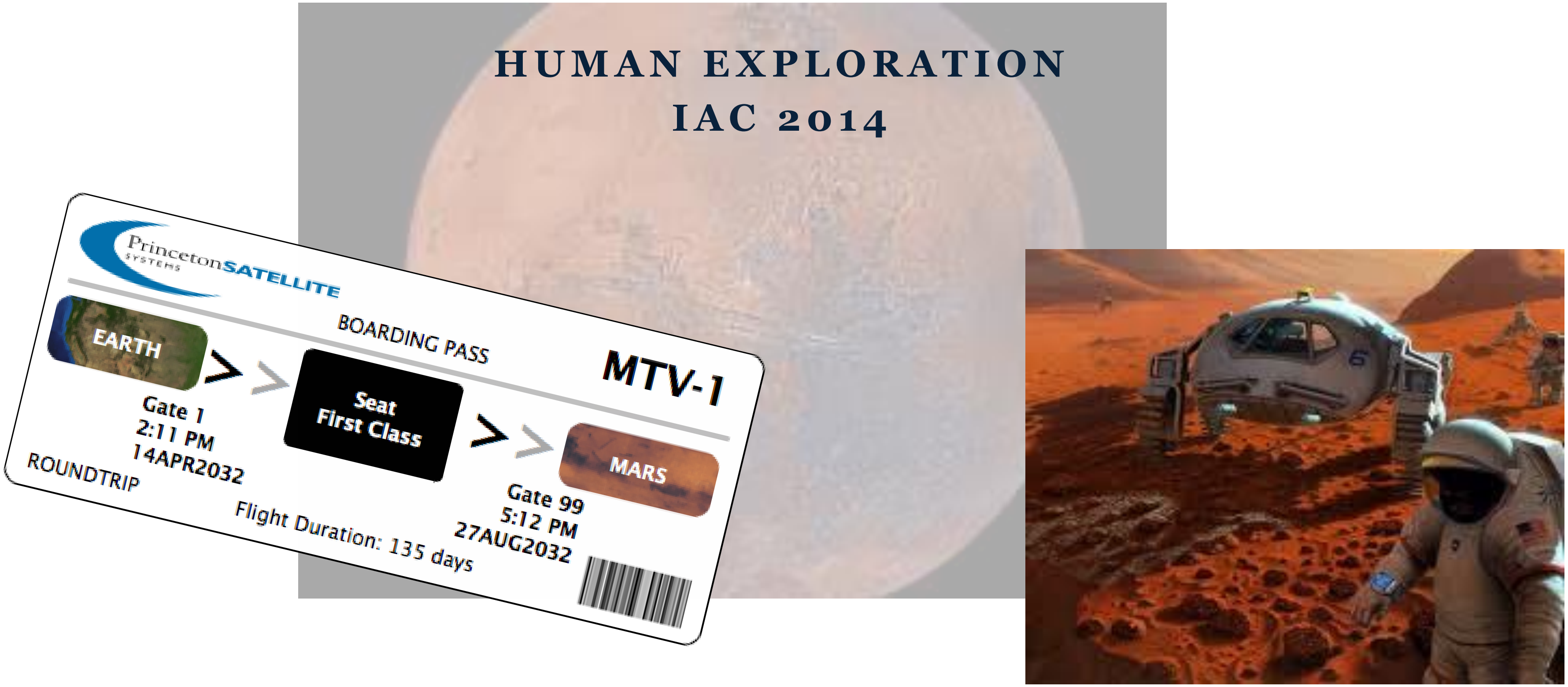




Apply 23 day **along-track** burn at perigee to optimally change SMA and create drift

Mars Mission

HUMAN EXPLORATION
IAC 2014



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BOARDING PASS

MTV-1

EARTH > > Seat First Class > > MARS

Gate 1
2:11 PM
14APR2032

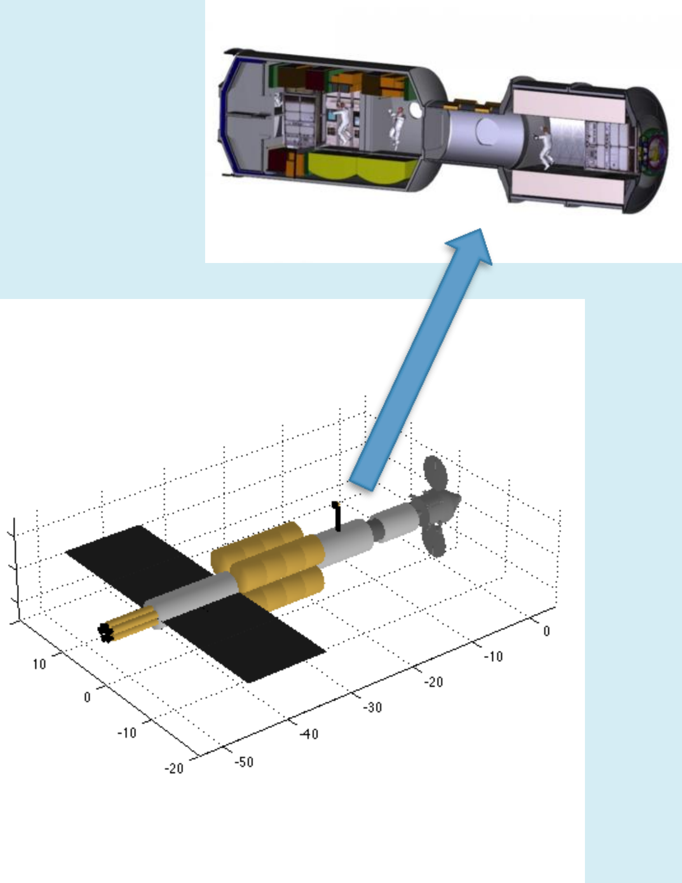
Gate 99
5:12 PM
27AUG2032

ROUNDTRIP

Flight Duration: 135 days

Synopsis: Mars Roundtrip

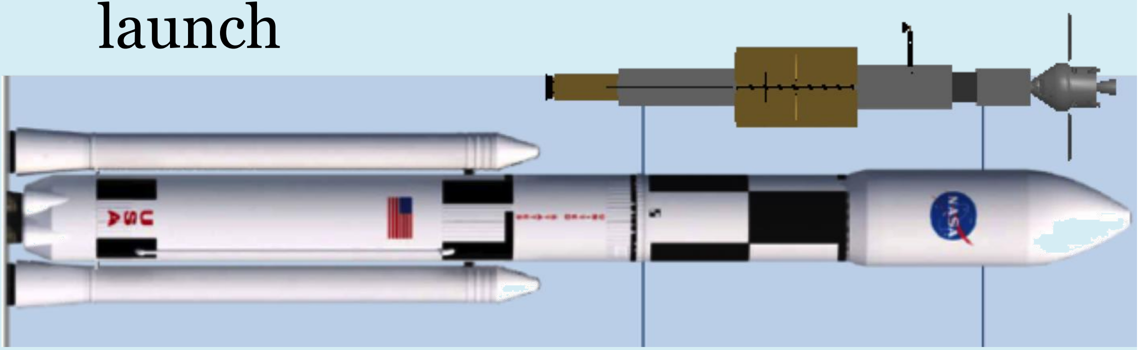
- Humans to Mars, orbit for several weeks and return to LEO
- Total ΔV of 50 km/s
- Trip time 310 days
- 30 MW engines
- Thrust ~ 300-400 N
- Total mass of 124 MT fits withing SLS envelope

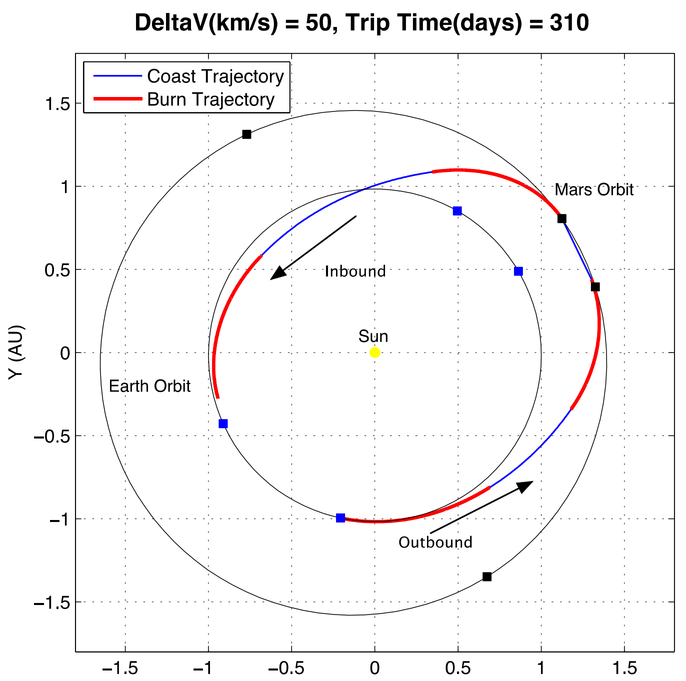


Mars transfer vehicle

Mars Trajectory and SLS

- Modified Lambert trajectory
  - 30 days in Mars orbit
  - 50 km/s and 310 days roundtrip
- 130 MT max for SLS Extended launch




DeltaV(km/s) = 50, Trip Time(days) = 310

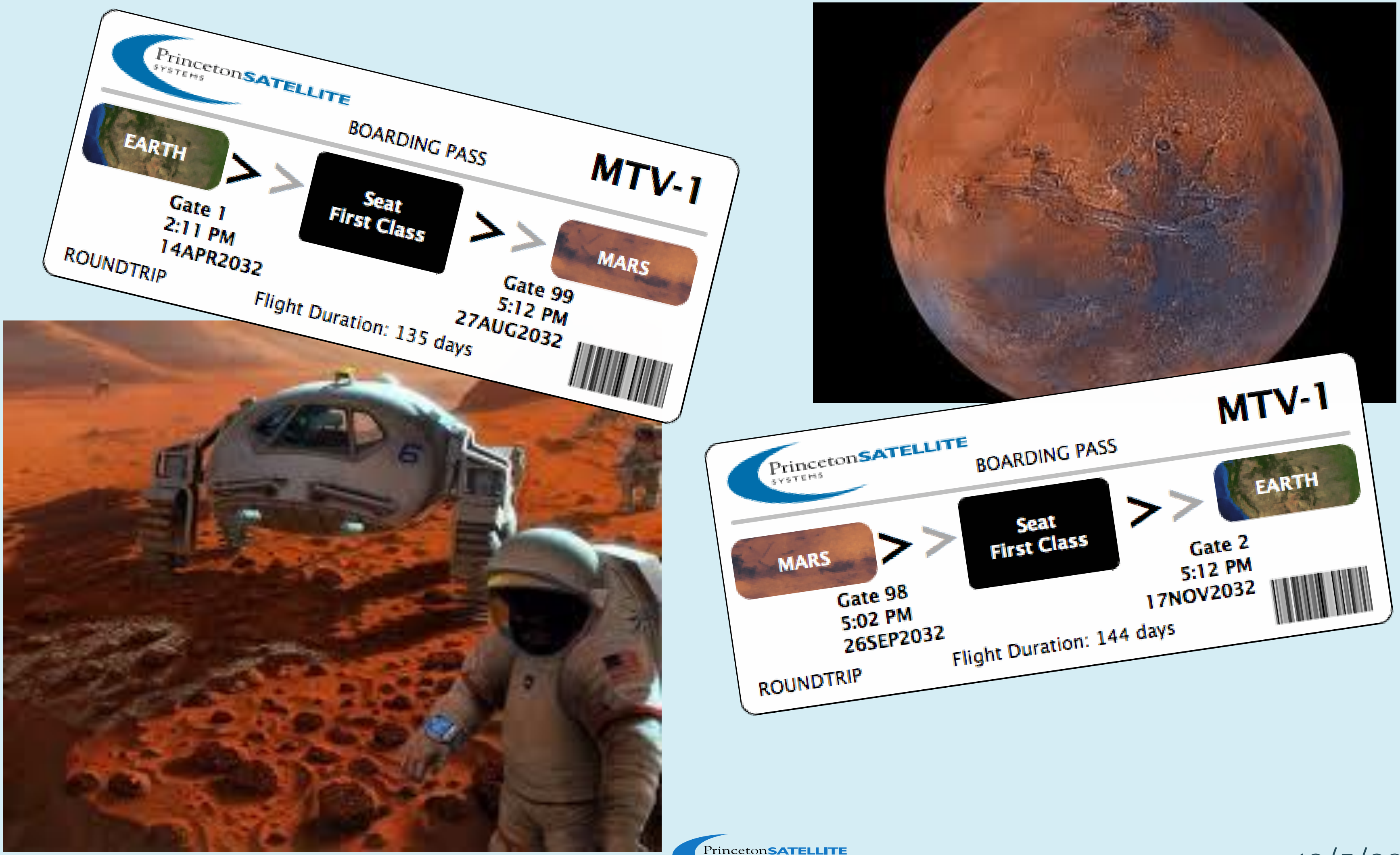
Type of Trajectory	Low Thrust Spiral	High Thrust Hohmann Transfer	Continuous Thrust	Lambert Solution (Ideal, not attainable)	Modified Fixed Burn Lambert
Roundtrip ΔV (km/s)	11.2	10.8	106.7	47.8	49.10
Total Trip Time	12 years	975 days	277.5 days	210 days	310 days

Conclusions

Conclusions

- DFD has the potential to enable many missions
  - Human Mars exploration with shorter flight durations, lower mass and abort capability
  - Game-changing power and capability for outer planet missions including asteroid deflection
  - Military applications for high-power Earth orbit missions
- Demonstration of a burning plasma possible in 10-12 years with enough funding, ~$50M
- Flight by 2032 possible
- Fusion may be closer than you think!

See you on Mars!



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BOARDING PASS

MTV-1

EARTH > > Seat First Class > > MARS

Gate 1
2:11 PM
14APR2032

Gate 99
5:12 PM
27AUG2032

ROUNDTRIP

Flight Duration: 135 days

PrincetonSATELLITE SYSTEMS

BOARDING PASS

MTV-1

MARS > > Seat First Class > > EARTH

Gate 98
5:02 PM
26SEP2032

Gate 2
5:12 PM
17NOV2032

ROUNDTRIP

Flight Duration: 144 days

For More Information

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- S. Cohen, G. Pajer, M. Paluszek and Y. Razin, "Method to Produce High Specific Impulse and Moderate Thrust From a Fusion-Powered Rocket Engine," PCT/US2013/40520, filed May 10, 2013.
- S. Cohen, G. Pajer, M. Paluszek and Y. Razin, "Method to Reduce Neutron Production in Small Clean Fusion Reactors," PCT/US13/33767, filed March 25, 2013.

Challenges of Direct Fusion Drive

- Need to demonstrate a burning plasma
  - PFRC-4
- Need to get Helium-3
  - Not that much needed, terrestrial sources have enough to support Mars exploration
  - Moon and gas giants are future sources
- Must minimize engine mass
  - Need high power per unit mass
- Need ways to startup the reactor in space
  - Recent provisional patent using a chemical rocket engine: Paluszek, Cohen, Ham
- Long duration cryogenic fuel storage in space
  - NASA has R&D in this area
- Need all the supporting hardware to be low mass and have high reliability
  - Ideally last for multiple missions
- Radiation shielding
  - Neutrons (but not too many)
  - Bremsstrahlung – x-rays
  - Synchrotron

DFD-Based Space Transportation Network

- DFD-powered space station
- ^{3}He mined on Moon, transported to station by DFD powered electromagnetic launchers
- Supports robotic missions, such as asteroid deflection and outer planet exploration
- Human missions to Mars, Asteroid Belt, and the Inner Planets