Fusion Propulsion

Opening the Solar System Frontier

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Lecture 28

Resources from Space

NEEP 533/ Geology 533 / Astronomy 533 / EMA 601

University of Wisconsin

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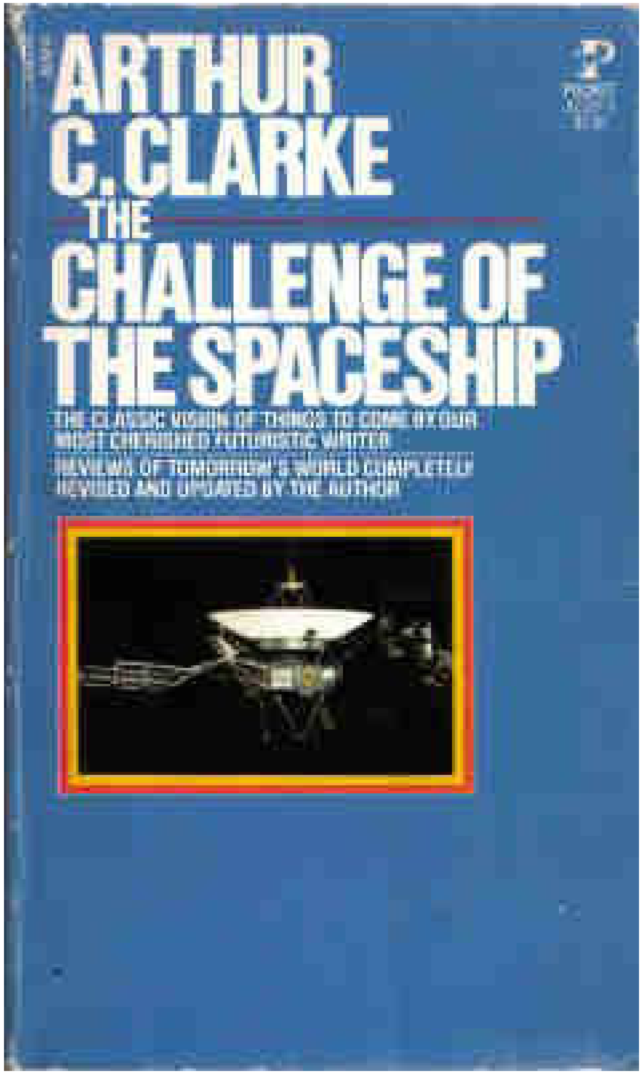
Key Points

- $D\text{-}^3He$ appears to be the fusion fuel of choice for space applications.
- $D\text{-}^3He$ fusion will provide capabilities not available from other propulsion options.
- Several configurations appear promising for space propulsion, particularly the field-reversed configuration (FRC), magnetized-target fusion (MTF), spheromak, and spherical torus.
- Successful development of $D\text{-}^3He$ fusion would provide attractive propulsion, power, and materials processing capabilities.

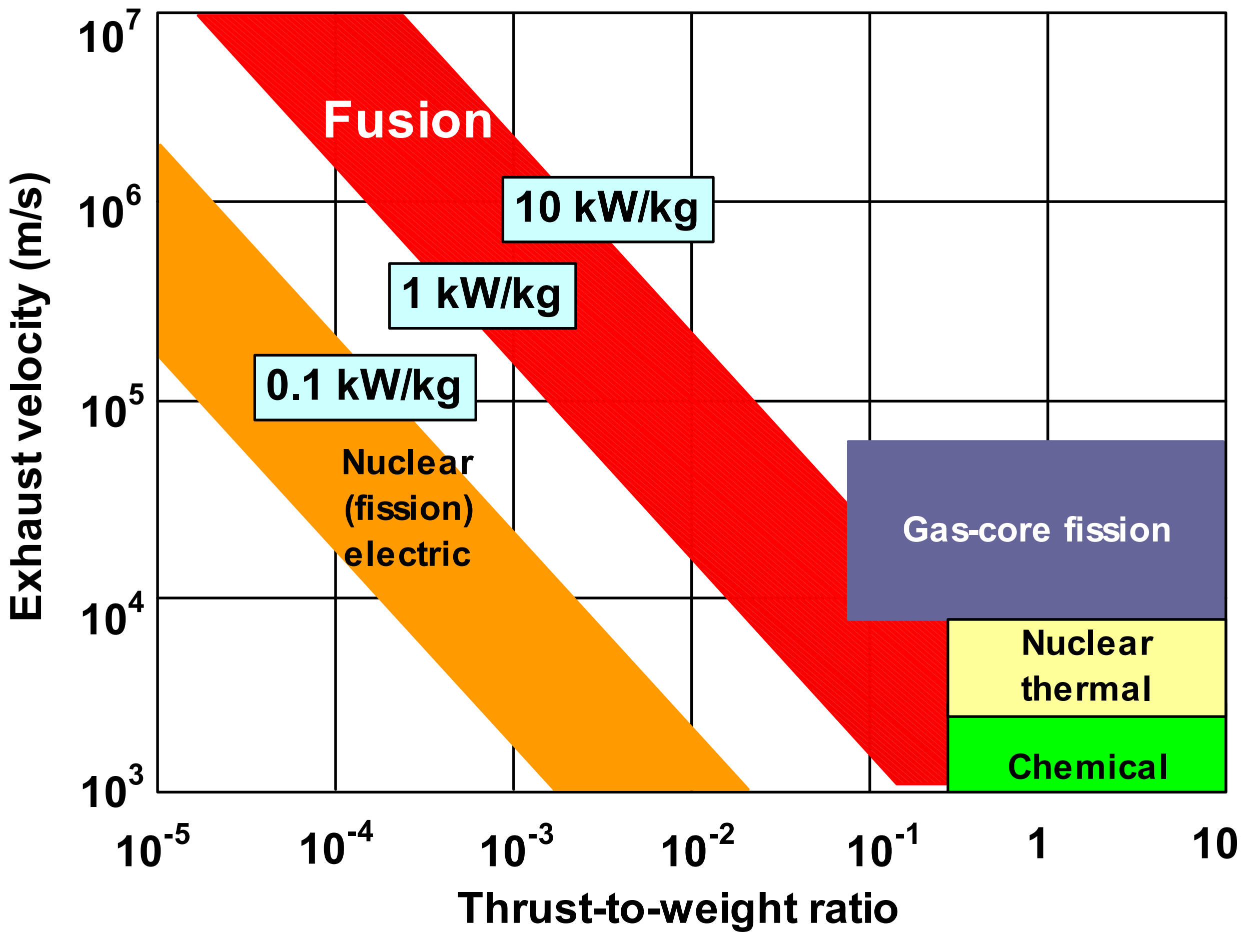
A Prophecy Whose Time Will Come

"The short-lived Uranium Age will see the dawn of space flight; the succeeding era of fusion power will witness its fulfillment."

From the essay "The Planets Are Not Enough" (1961).



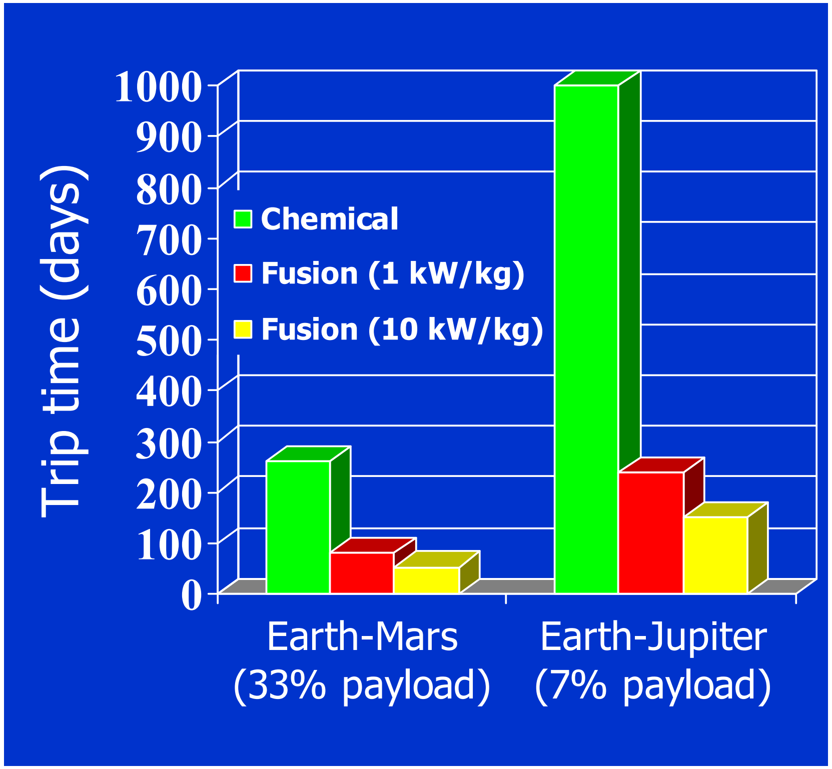
D-^{3}He Fusion Will Provide Capabilities Not Available from Other Propulsion Options



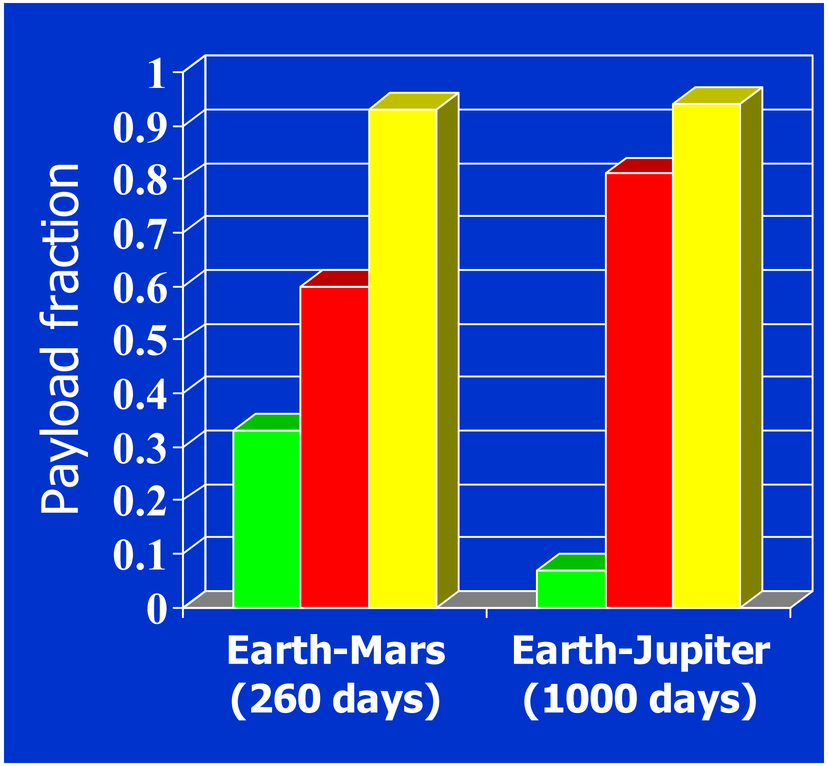
At the Predicted Specific Power, α=1-10 kW/kg, Fusion Propulsion Would Enable Attractive Solar-System Travel

- Comparison of trip times and payload fractions for chemical and fusion rockets:

Fast human transport



Efficient cargo transport



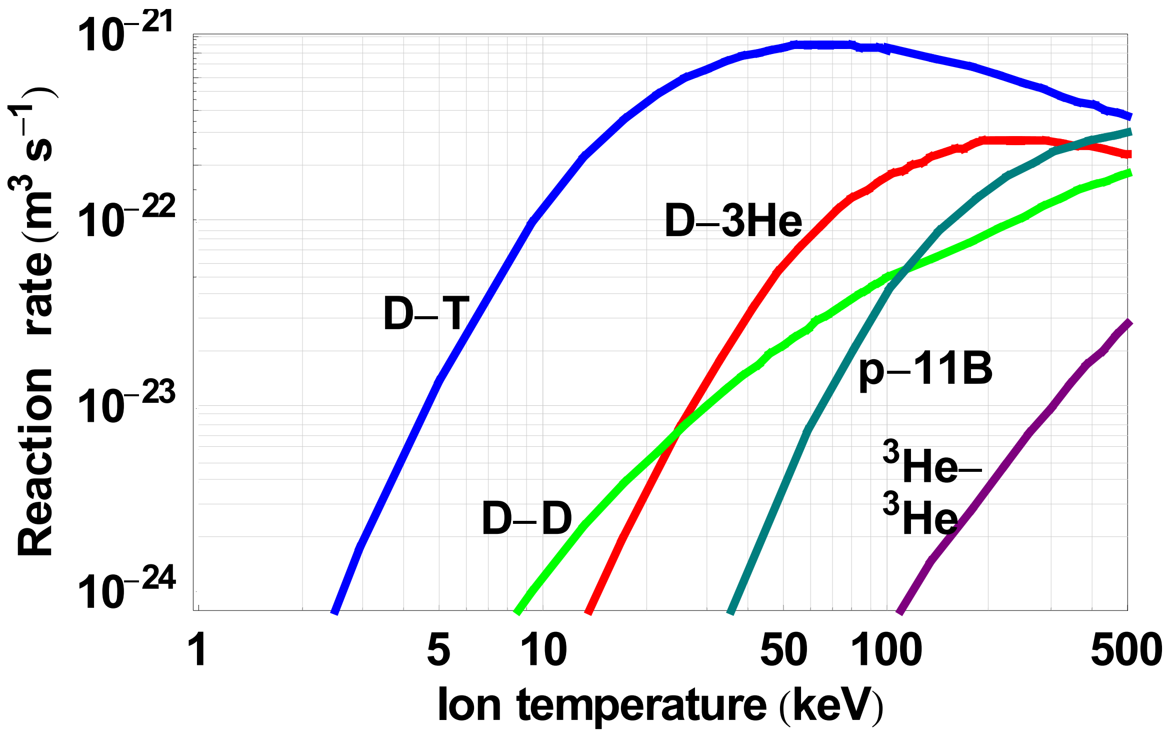
Key Fusion Fuel Cycles for Space Applications

$D + {}^3He \rightarrow p\ (14.68\ MeV) + {}^4He\ (3.67\ MeV)$

$D + T \rightarrow n\ (14.07\ MeV) + {}^4He\ (3.52\ MeV)$

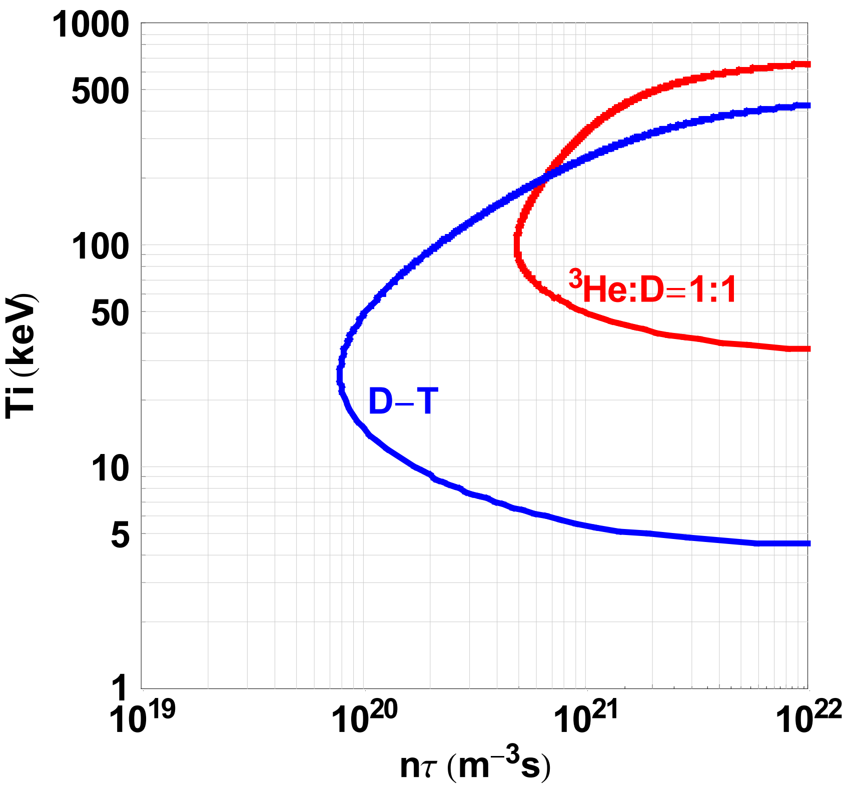
$D + D \rightarrow n\ (2.45\ MeV) + {}^3He\ (0.82\ MeV)$ {50%}

$\rightarrow p\ (3.02\ MeV) + T\ (1.01\ MeV)$ {50%}

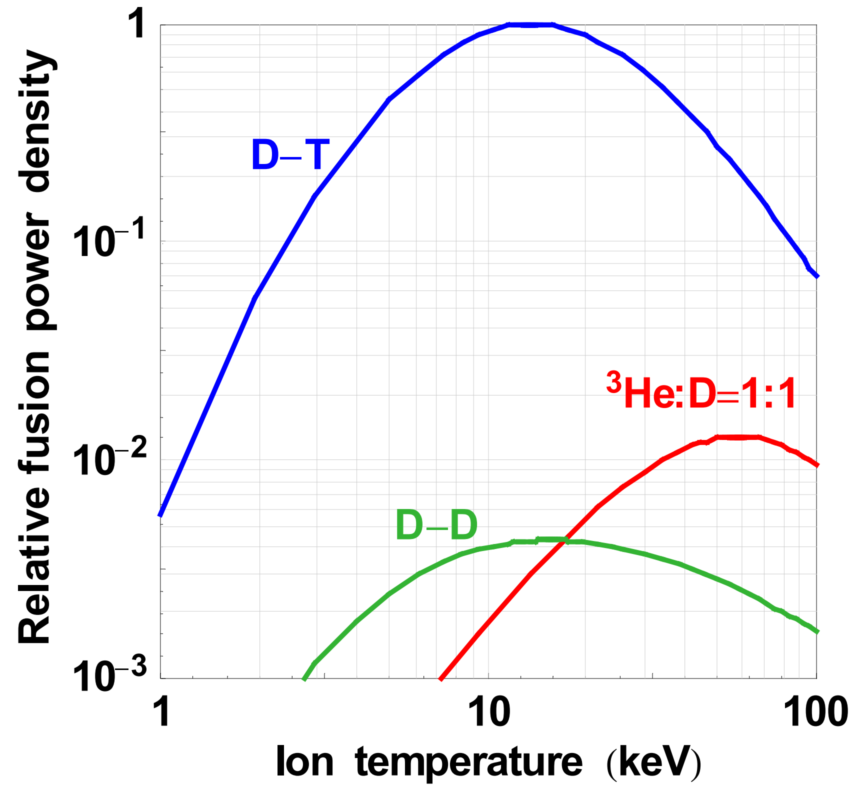


Physics Viewpoint:
D-^{3}He Fuel Requires High β, nτ, and T†

Confinement



Power density

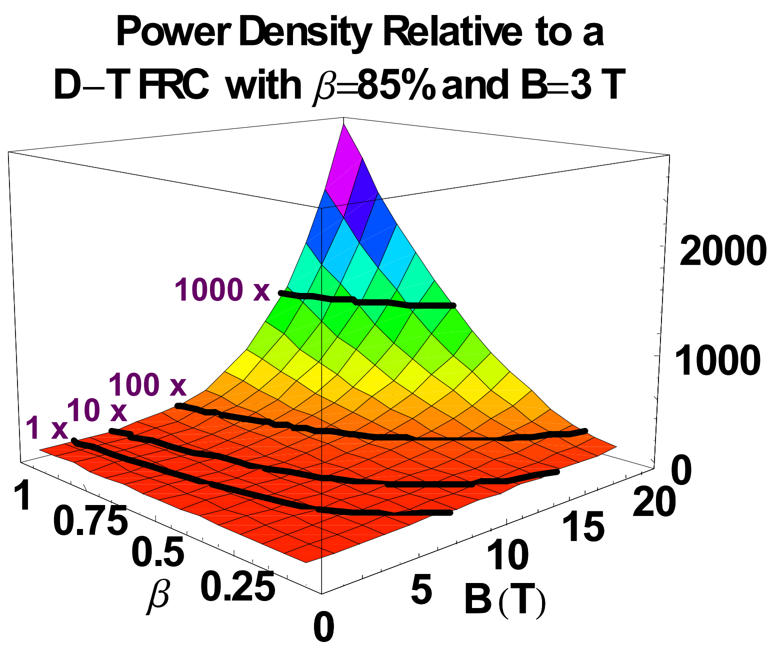


† β = plasma pressure/magnetic field pressure

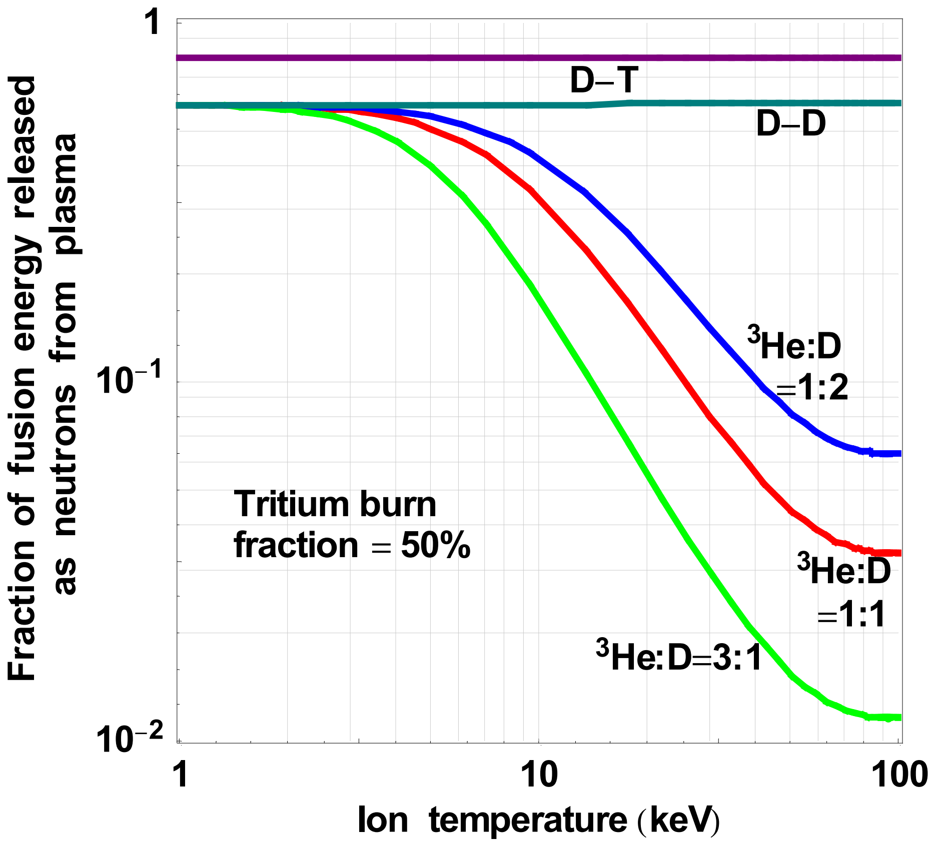
τ = energy confinement time

D-^{3}He Fuel Could Make Good Use of the High Power Density Capability of Some Innovative Fusion Concepts

- D-T fueled innovative concepts become limited by neutron wall loads or surface heat loads well before they reach β or B-field limits.
- D-T fueled FRC's (β~85%) optimize at B ≤ 3 T.
- D-^{3}He needs a factor of ~80 above D-T fusion power densities.
  - Superconducting magnets can reach at least 20 T.
  - Fusion power density scales as $\beta^2 B^4$.
  - Potential power-density improvement by increasing β and B-field appears at right.



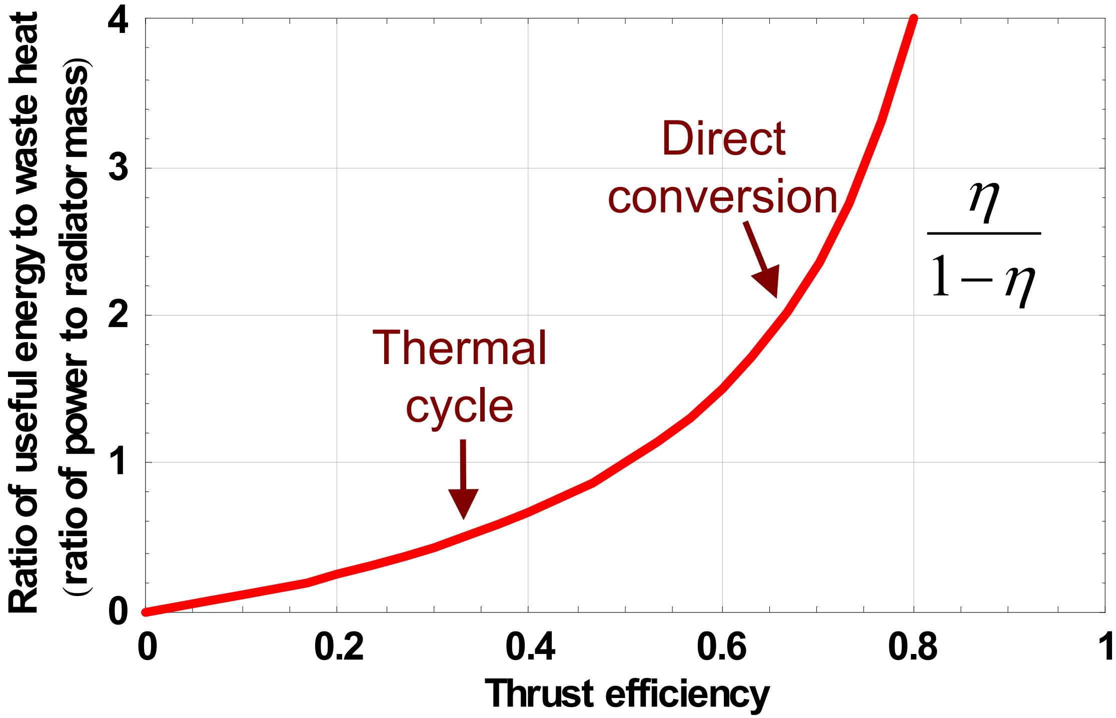
Engineering Viewpoint: D-^{3}He Fuel and High β Relax Constraints



- Reduced neutron flux allows
  - Smaller radiation shields
  - Smaller magnets
  - Less activation
  - Easier maintenance
- Increased charged-particle flux allows direct energy conversion to thrust or electricity

Spacecraft Mass Gains Nonlinearly with Thrust Efficiency

- High efficiency increases thrust power and reduces radiator mass.



- Doubling efficiency from a thermal cycle's ~1/3 to direct conversion's ~2/3 gives 4 times better power per unit waste heat.

Predicted Specific Power of D-^{3}He Magnetic Fusion Rockets is 1-10 kW/kg

- Prediction based on reasonably detailed magnetic fusion rocket studies.

First Author	Year	Configuration	Specific Power (kW/kg)
Borowski	1987	Spheromak	10.5
Borowski	1987	Spherical torus	5.8
Santarius	1988	Tandem mirror	1.2
Bussard	1990	Riggatron	3.9
Teller	1991	Dipole	1.0
Nakashima	1994	Field-reversed configuration	1.0
Williams	2003	Spherical torus	8.7
Thio	2002	Magnetized-target fusion	50
Emrich	2000	Gasdynamic mirror	130
Wessel	2000	Colliding-beam FRC	1.5

Generic Fusion Rocket Model Supports 1-10 kW/kg

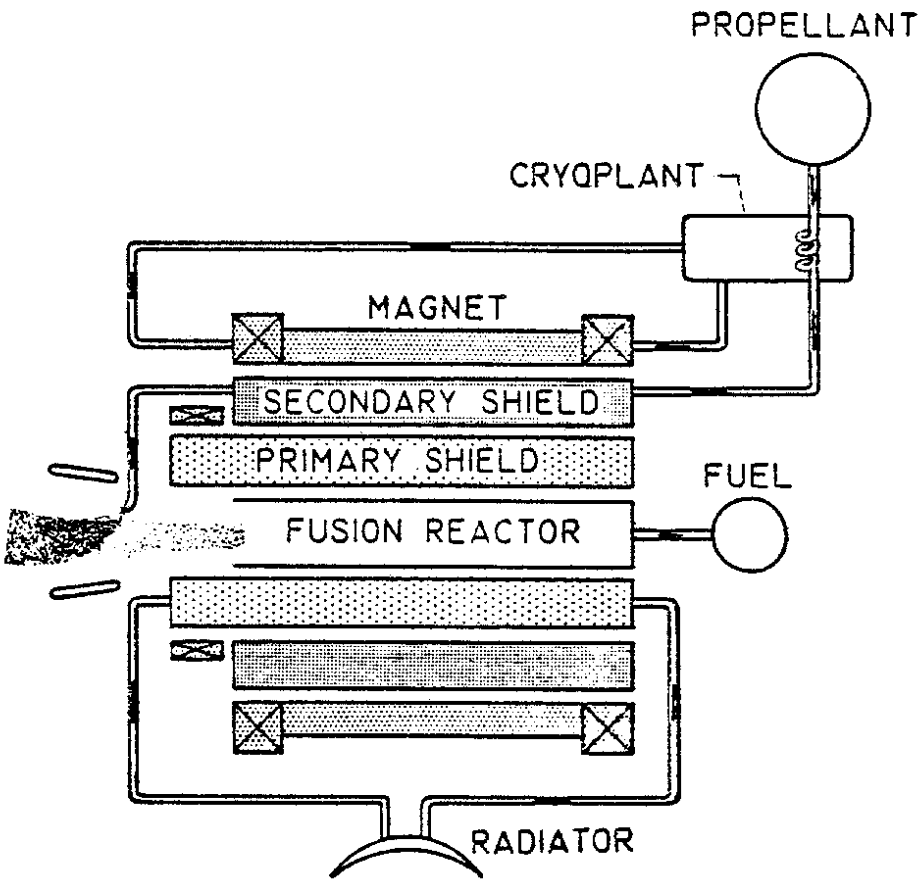
- Rationale for this performance published by J.F. Santarius and B.G. Logan, "Generic Magnetic Fusion Rocket," *Journal of Propulsion and Power* **14**, 519 (1998). Features of the model are:
  - Cylindrical geometry
  - Main mass contributors: radiation shields, magnets, refrigerators, and radiators
  - Heat flux limit of 5-10 MW/m^2
  - Neutron wall load limit of 20 MW/m^2
  - Radiators reject 5 kW/kg
  - Low temperature superconducting magnet He refrigerators require 1000 $kg/kW_{rejected}$
  - Low-mass radiation shield (LiH with 10% Al structure)
  - Magnet mass calculated by virial theorem and by winding-pack current density limit (50 MA/m^2); larger value used
  - Development of high-temperature superconductors should reduce the power-plant mass.
    - Reduced refrigerator mass for magnet coolant
    - Reduced shielding, because more magnet heating can potentially be tolerated before quenching

Earliest D-^{3}He Reactor Design Was a Fusion Rocket

G.W. Englert,
NASA Glenn Research Center
New Scientist (1962)

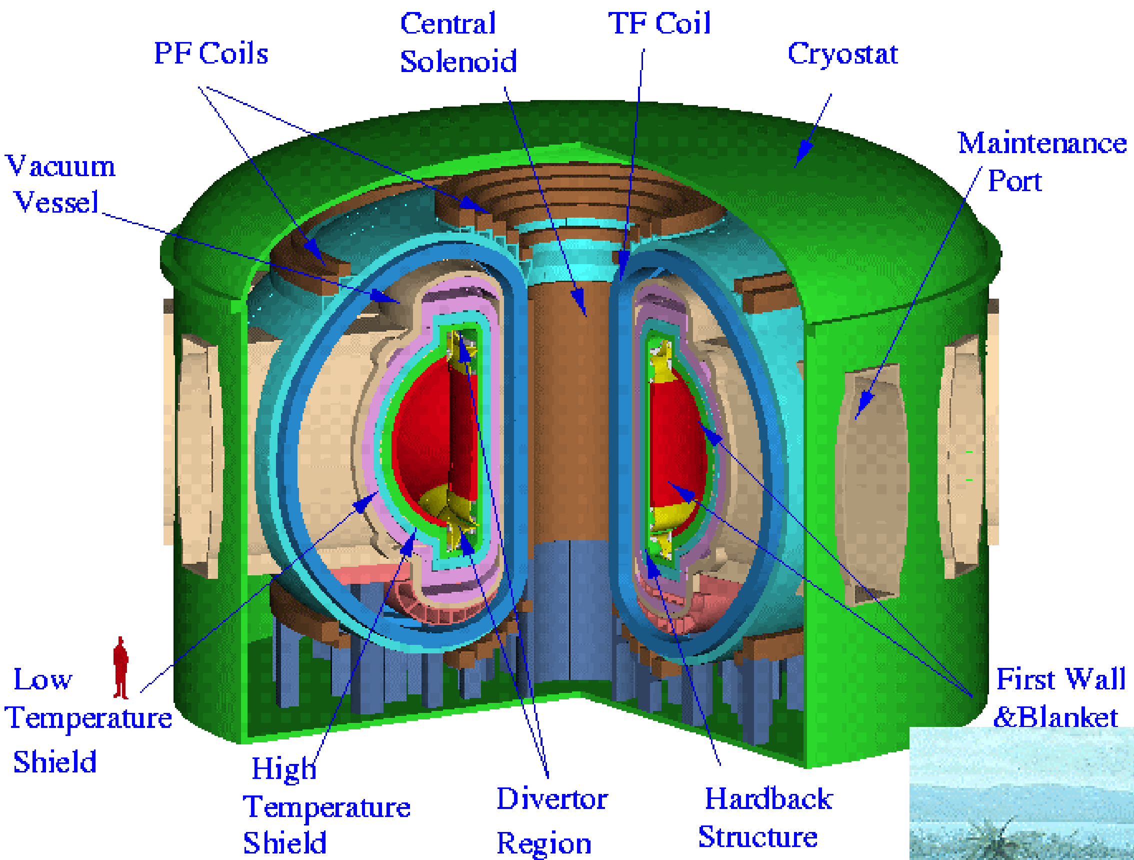
"If controlled thermonuclear fusion can be used to power spacecraft for interplanetary flight it will give important advantages over chemical or nuclear fission rockets.

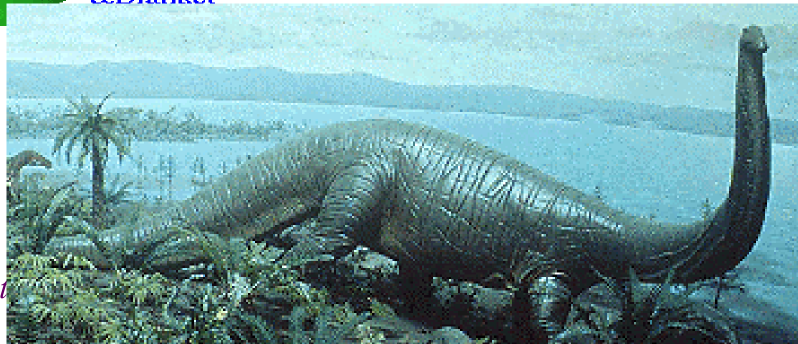
The application of superconducting magnets and a mixture of deuterium and helium-3 as fuel appears to be the most promising arrangement."



Conventional Tokamaks Have Large Mass

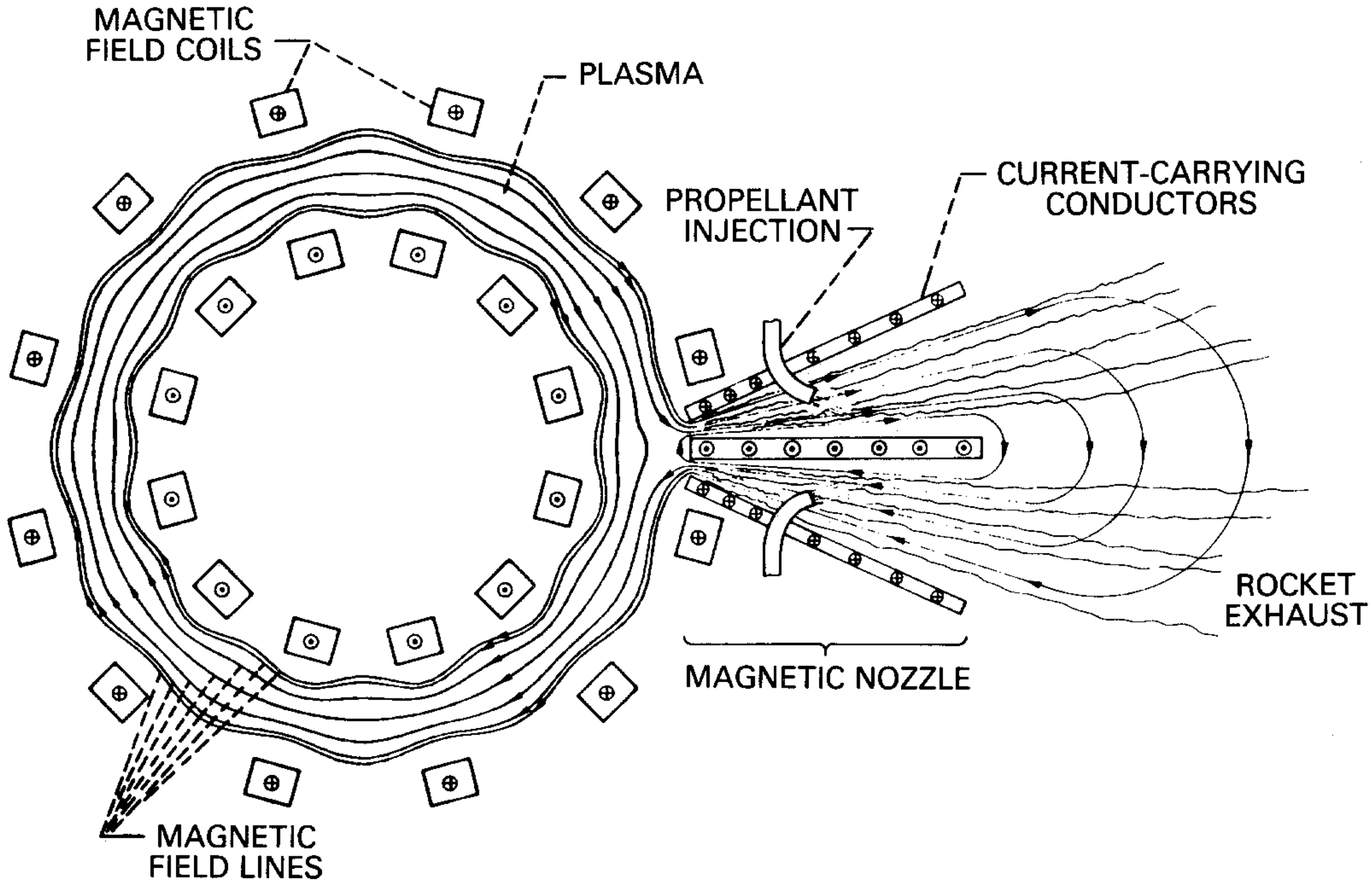
Cutaway of the ARIES-RS Power Core





EFBT Toroidal Fusion Rocket

J. Reece Roth, NASA Lewis, 1972

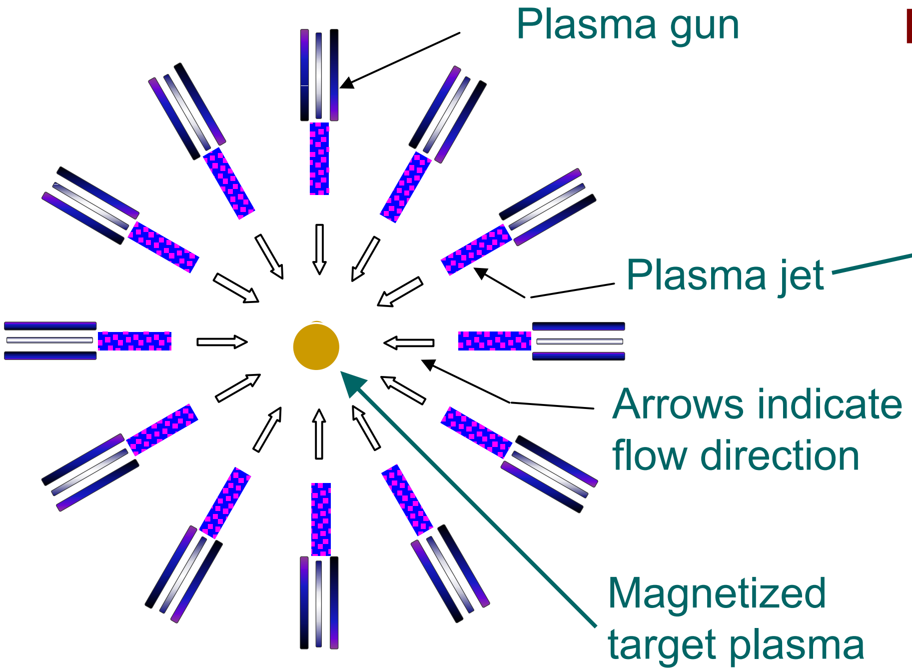


Spherical Torus Space Propulsion

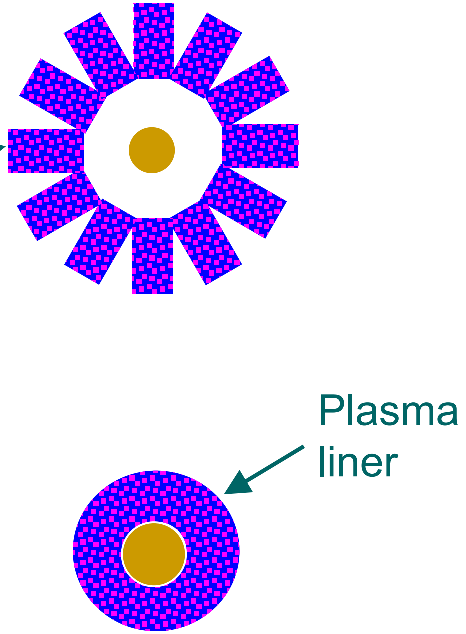
- ST's give high β, implying high power density.
- Crucial problems are recirculating power and providing thrust from a toroidal configuration.
- Martin Peng has suggested helicity *ejection*, and the concept will be tried on NSTX.

Princeton Plasma Physics Lab NSTX experiment

Plasma-Jet Magnetized-Target Fusion Allows Liner Standoff from Target



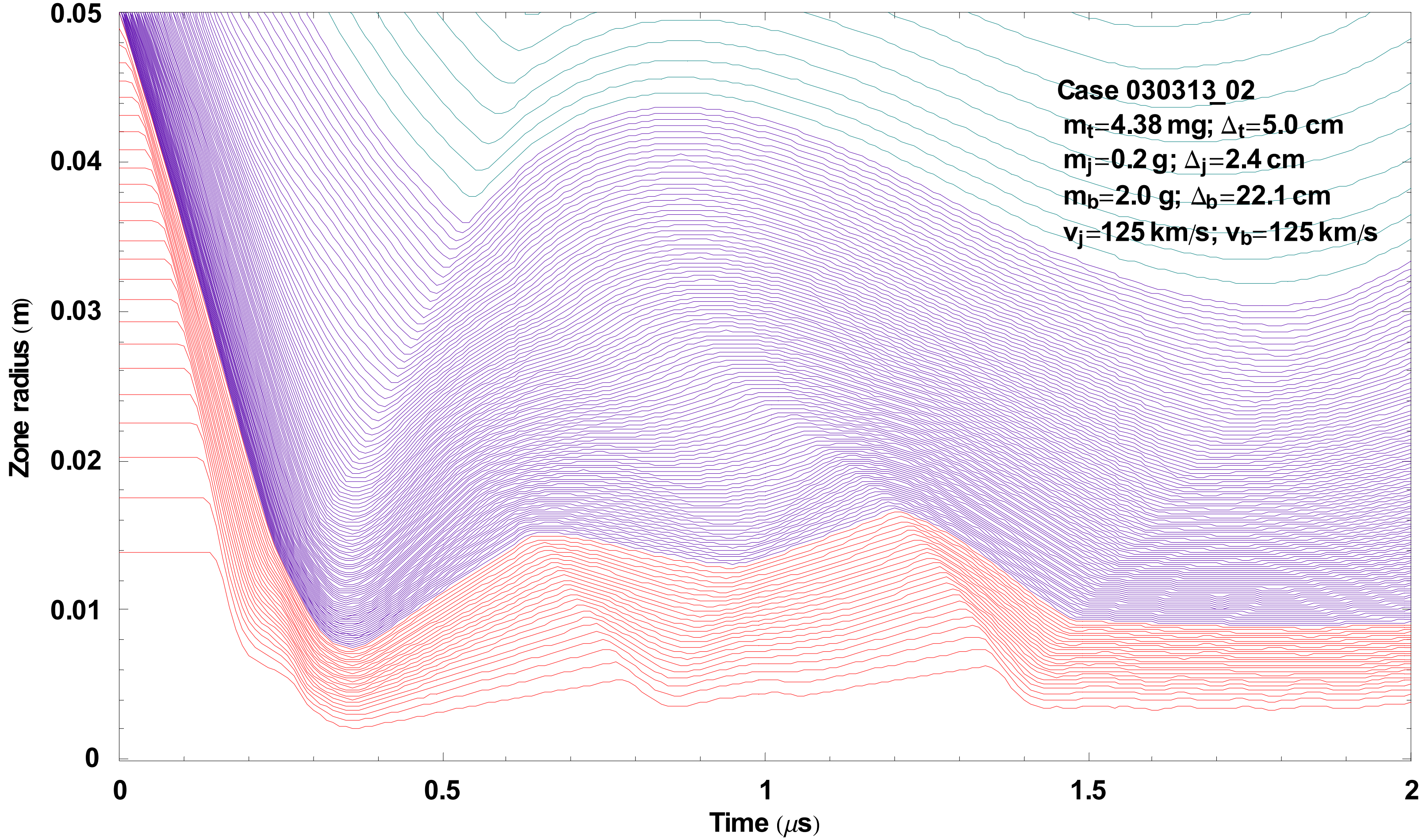
Based on NASA MSFC figures



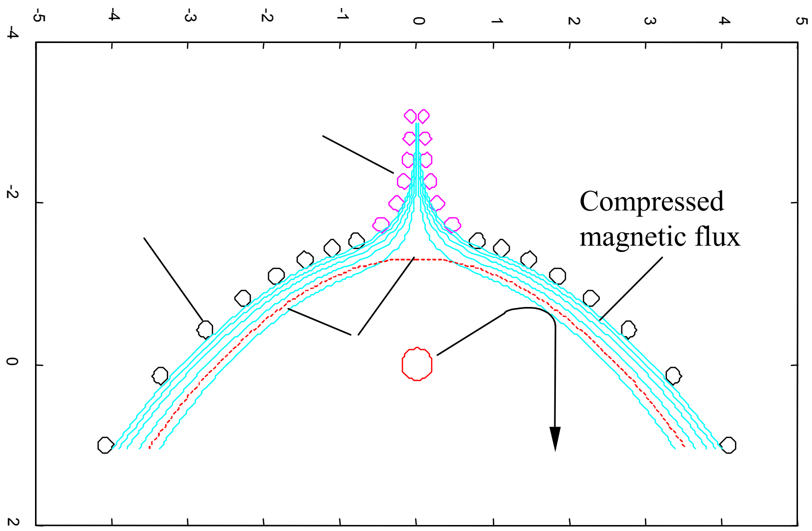
- An approximately spherical distribution of jets is launched towards the compact toroid at the center of a spherical vessel.
- The jets merge to form a spherical shell (liner), imploding towards the center.

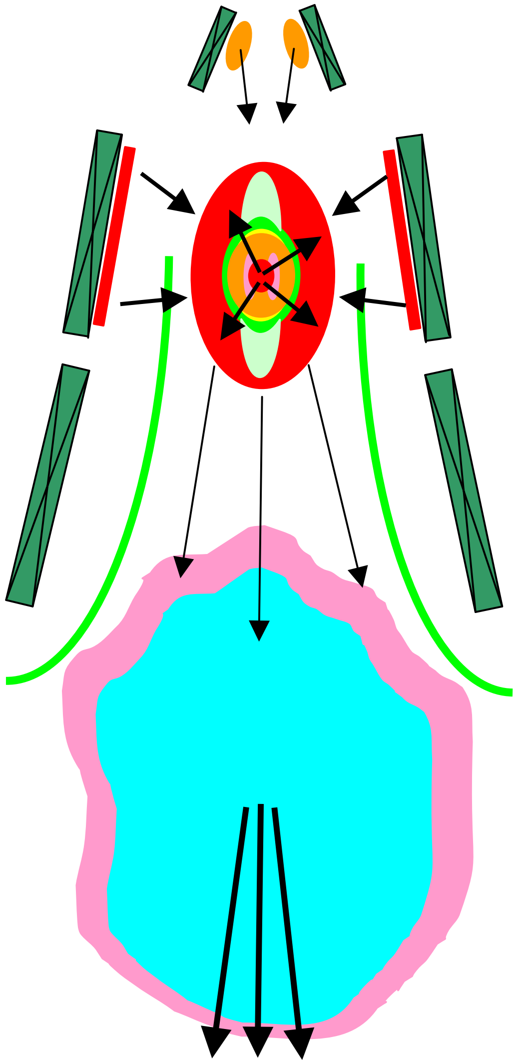
The MTF Explosion/Implosion Process Involves a Complicated Mixture of Shock Waves

- Red=target; Purple=plasma jet; Green=buffer plasma



Conversion of Fusion Energy into Thrust

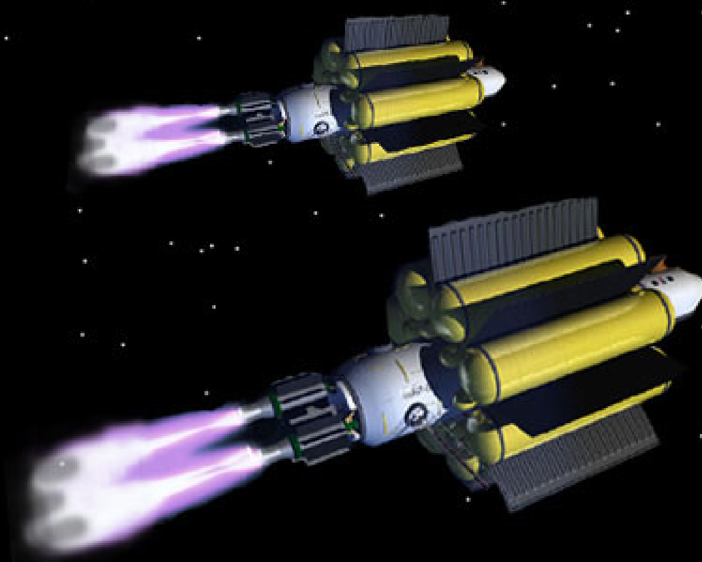




- Fusion produces a high-temperature plasma, which can be used to push against a magnetic field to produce thrust directly.
- Direct conversion of the fusion energy into thrust is important in realizing the benefits of fusion for propulsion.

NASA MSFC

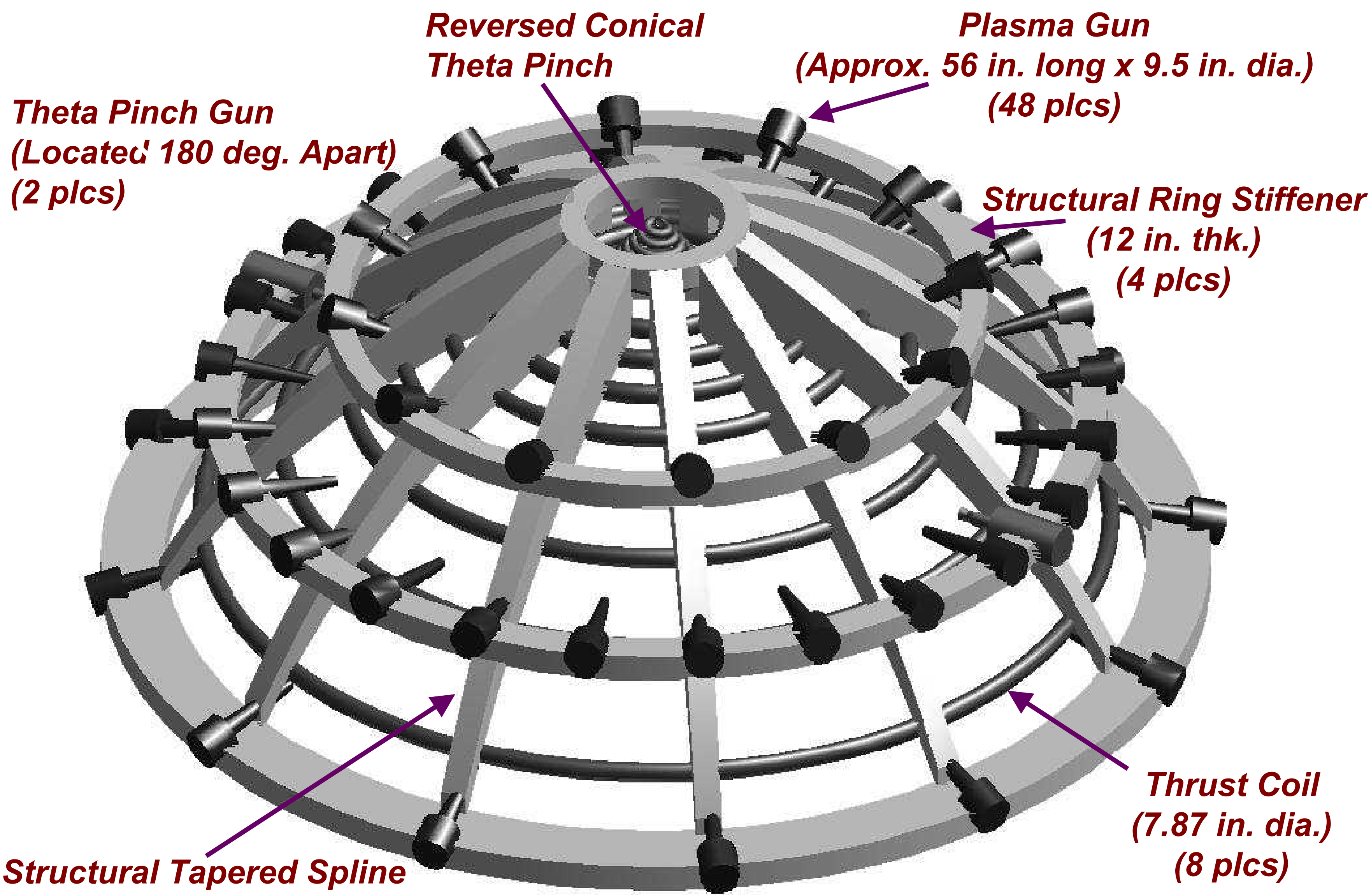
Revolutionary Aerospace Systems Concepts (RASC) FY02 Study Proposal



Group 2 – Human Exploration Beyond Mars

October 2, 2001

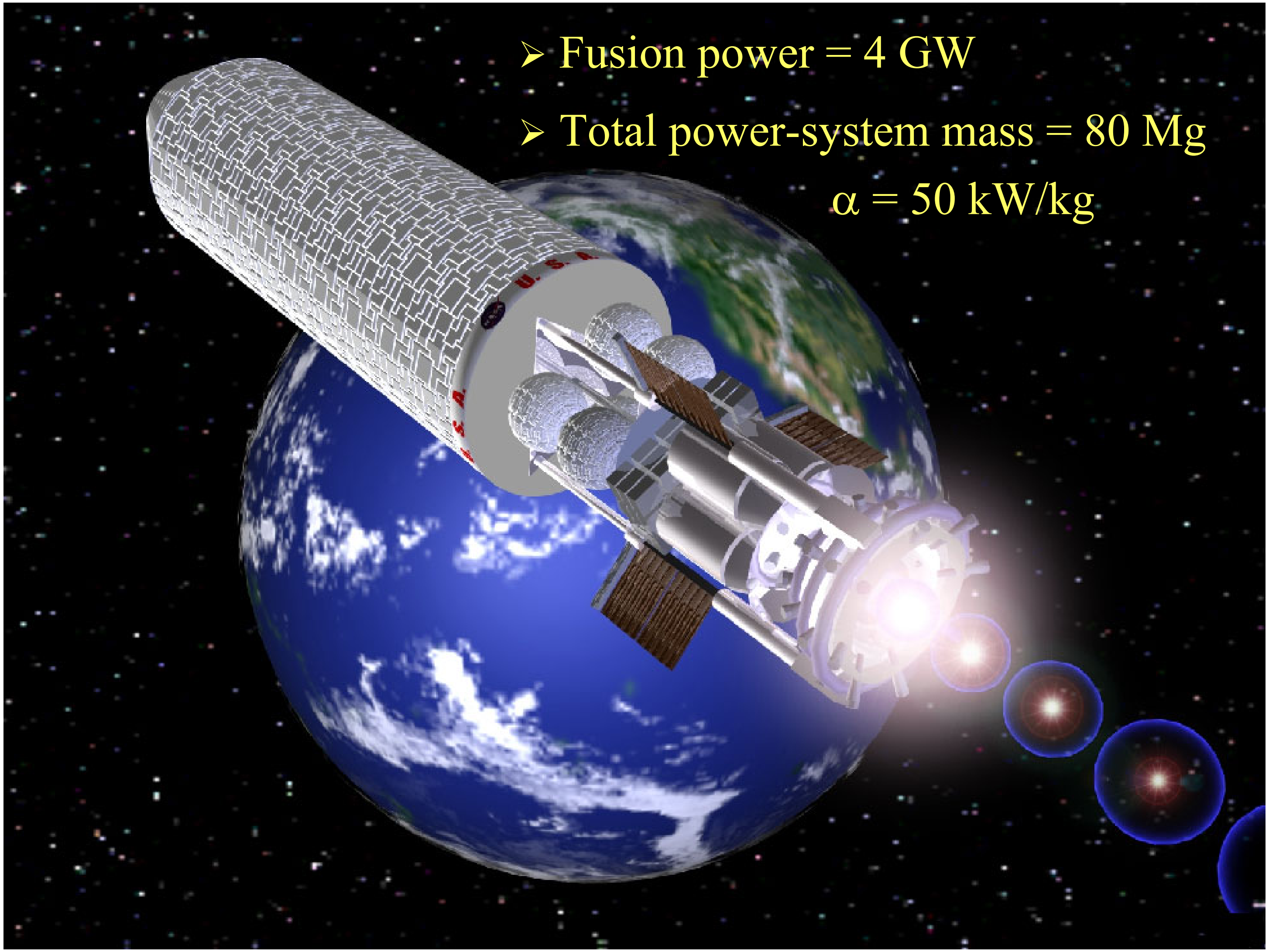
RASC/HOPE MTF Engine Configuration



NASA MSFC

TD30/Fincher
7/31/02

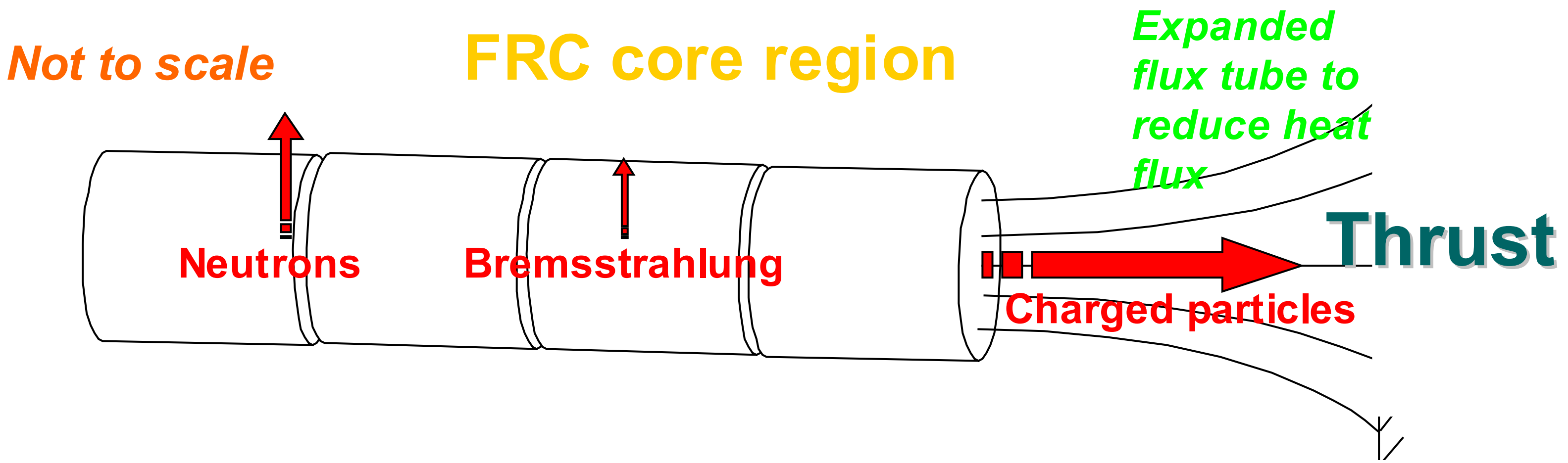
NASA Produced a Conceptual MTF Rocket Design



- Fusion power = 4 GW
- Total power-system mass = 80 Mg
  α = 50 kW/kg

Plasma Power Flows in Linear Devices Differ Significantly from Flows in Toroidal Devices

- Power density can be very high due to $\beta^2 B^4$ scaling, but first-wall heat fluxes would remain manageable.
  - Charged-particle power transports from internal plasmoid to edge region and then out ends of fusion core.
  - Magnetic flux tube can be "pinched" on one end by increasing the magnetic field on that side, giving primarily single-ended flow.

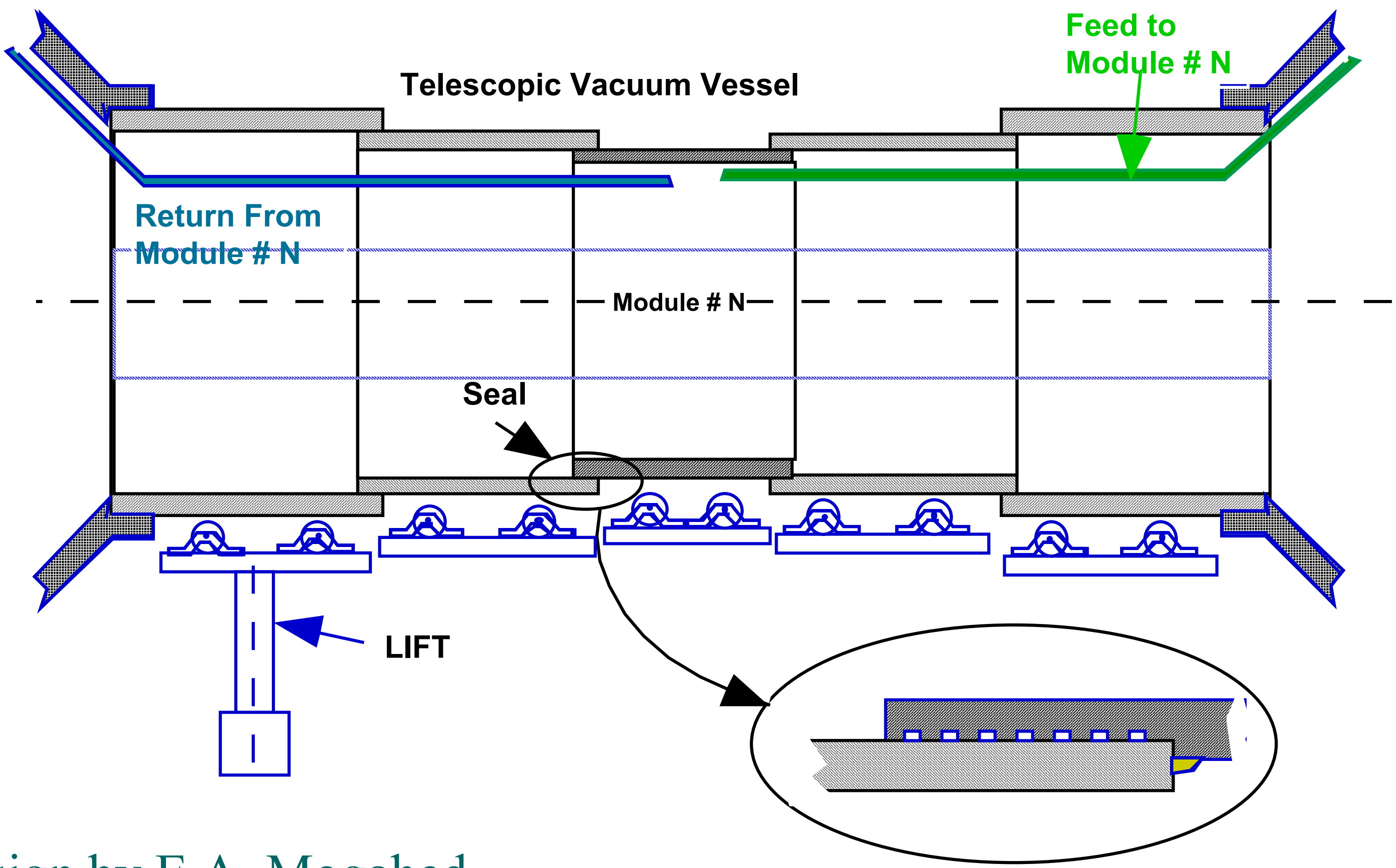


Linear Geometry Greatly Facilitates Engineering

- Steady-state heat flux is broadly spread and due almost exclusively to bremsstrahlung radiation power.
  - ➢ Relatively small peaking factor along axis for bremsstrahlung and neutrons.
- Maintenance of single-unit modules containing blanket, shield, and magnet should be relatively easy, improving reliability and availability.
- Considerable flexibility and space exist for placement of pipes, manifolds, etc.
- Direct conversion of transport power to thrust by a magnetic nozzle can increase efficiency.

Radioactivity Will Most Likely Lead to a Requirement for Remote Maintenance

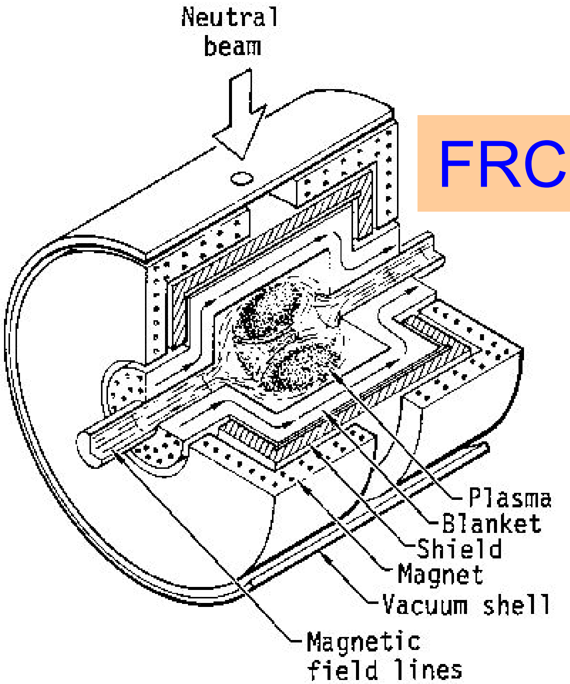
Maintenance Scheme for a Terrestrial-Electric FRC Using a Telescopic Vacuum Vessel



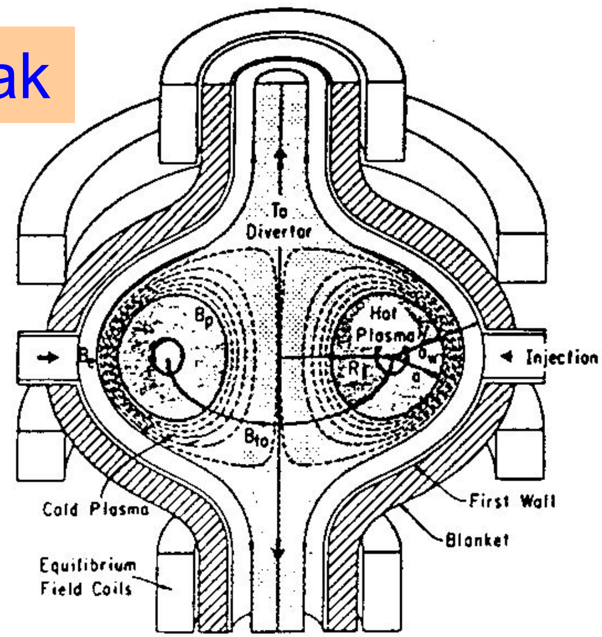
- Design by E.A. Mogahed

Several Concepts with Linear External Magnetic Fields Have Been Investigated for Space Propulsion

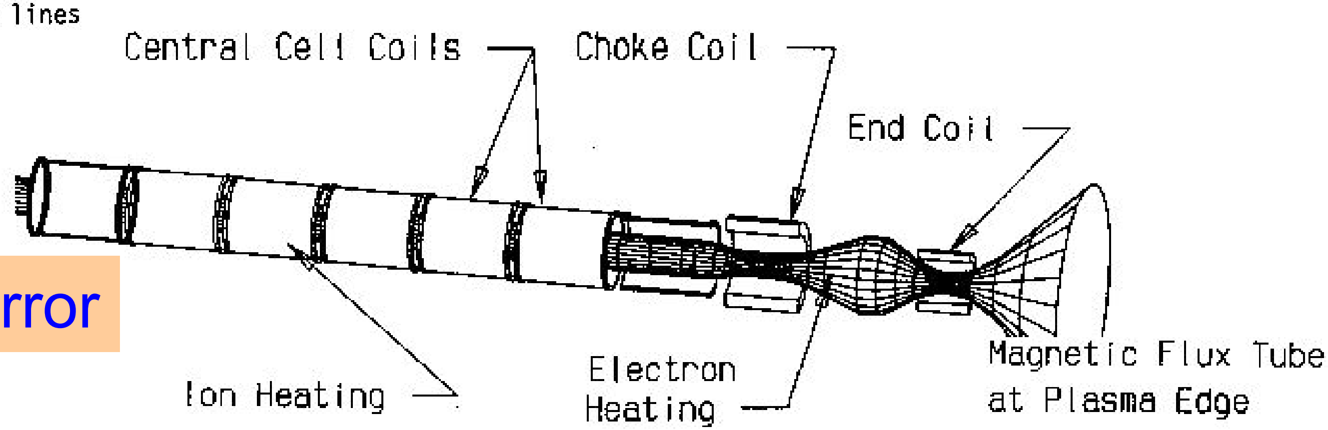
FRC



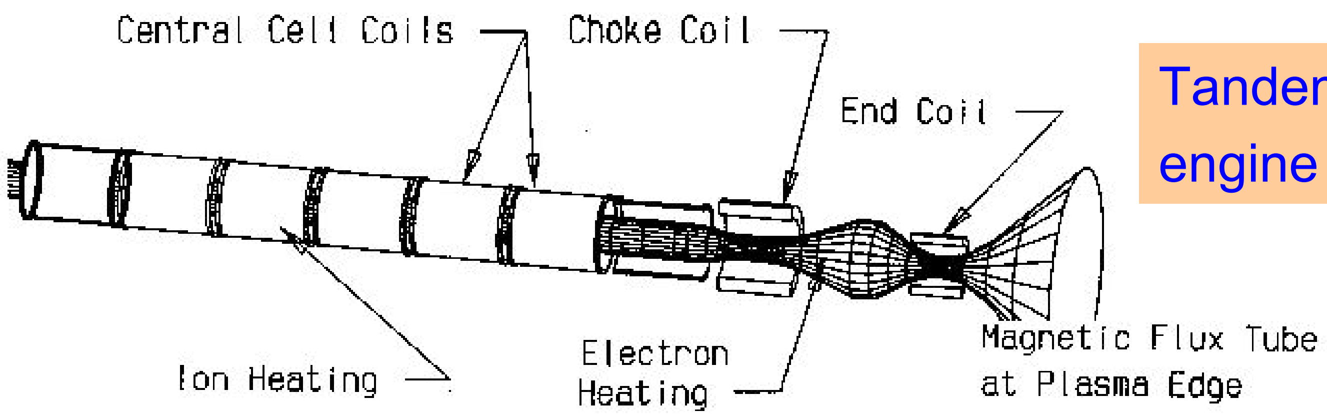
Spheromak



Tandem mirror



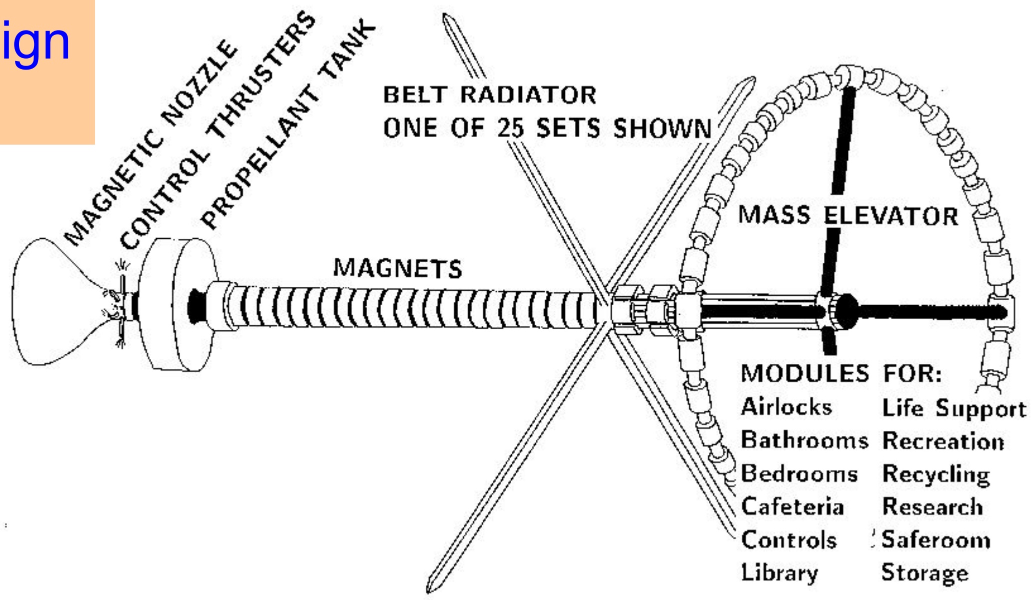
D-^{3}He Space-Propulsion Tandem Mirror



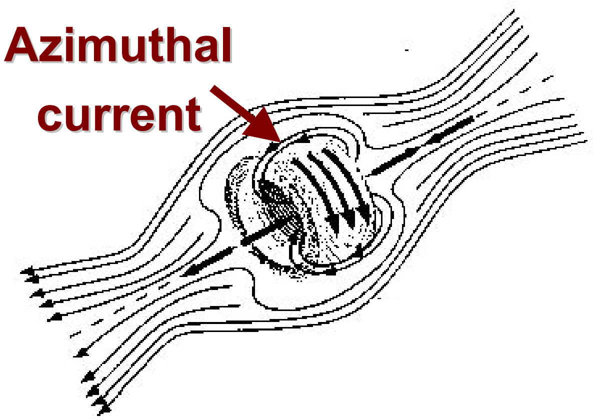
Tandem mirror engine

Tandem mirror rocket design by UW EMA 569 students

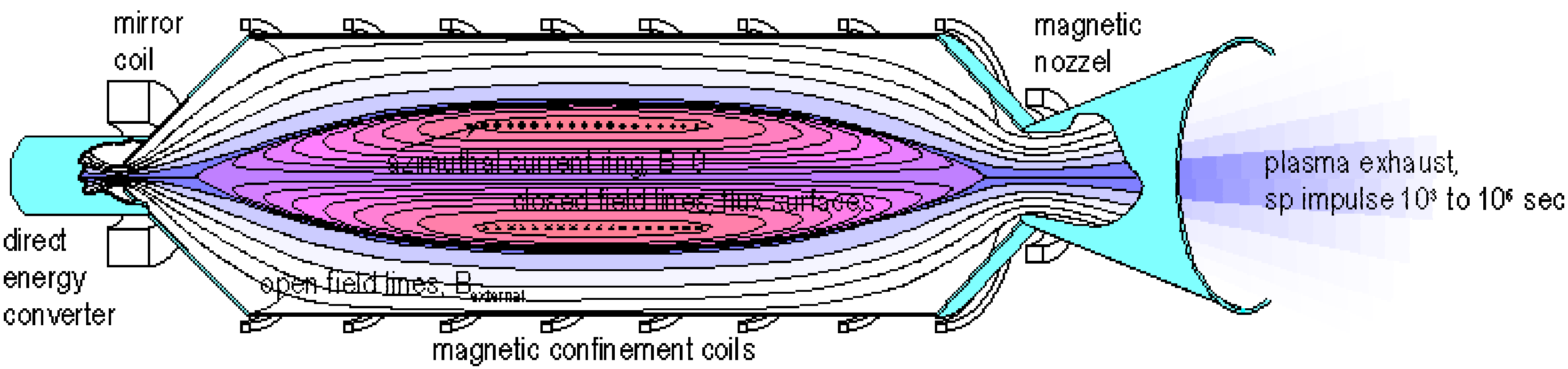
Specific power	1.2 kW/kg
Thrust power	1500 MW
Length	113 m
Ave. outer radius	1 m
Core B field	6.4 T



Field-Reversed Configurations (FRC) Would Be Attractive for Space Applications



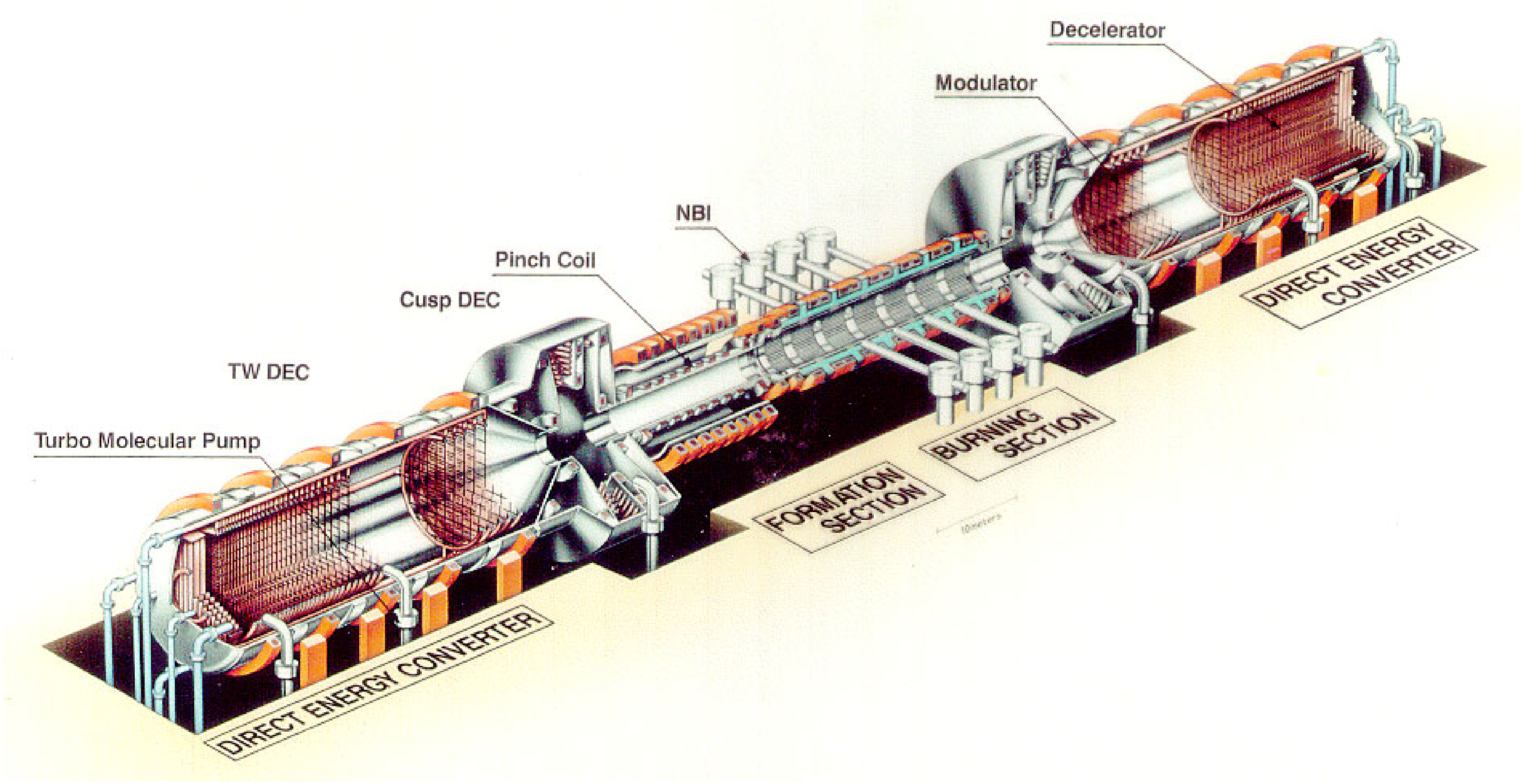
- High $\beta \equiv P_{plasma}/P_{B\text{-field}}$
- Linear external B field
- Cylindrical geometry
- Rotating B field current drive



FRC as Power Source and Ion Engine for High Energy Space Missions

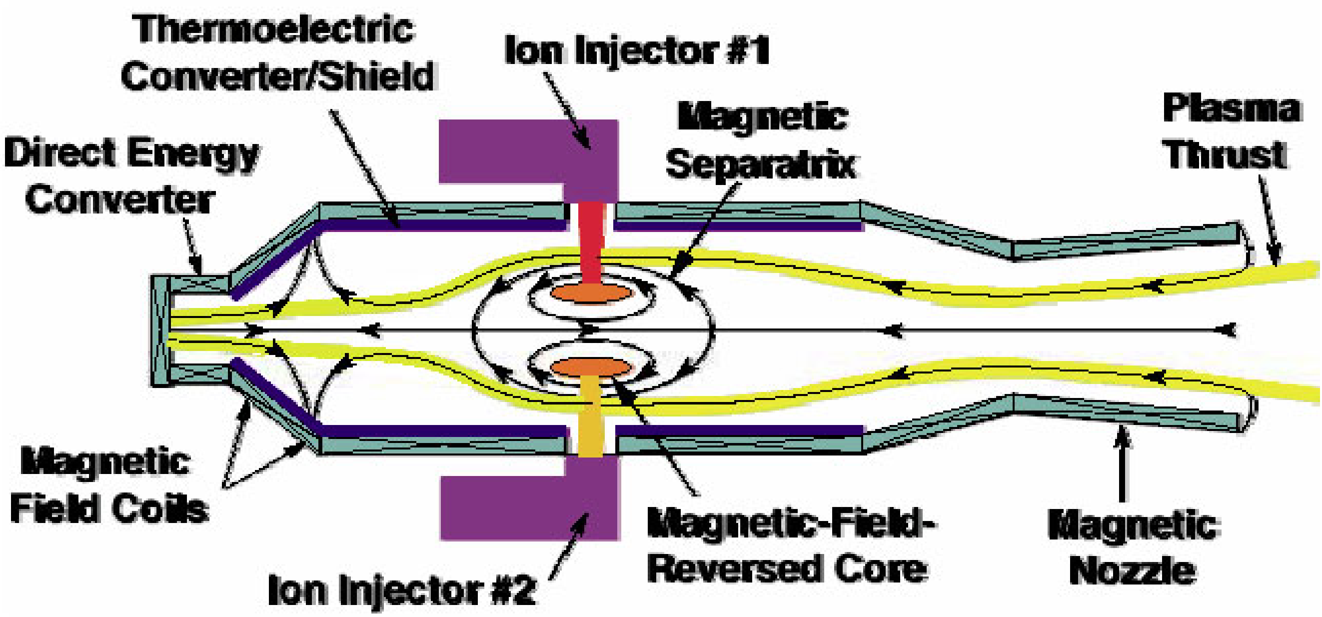
From Univ. of Washington web page for the Star Thrust Experiment (STX):
www.aa.washington.edu/AERP/RPPL/STX.html

ARTEMIS Field-Reversed Configuration (D-^{3}He, Momota, et al., NIFS, 1992)



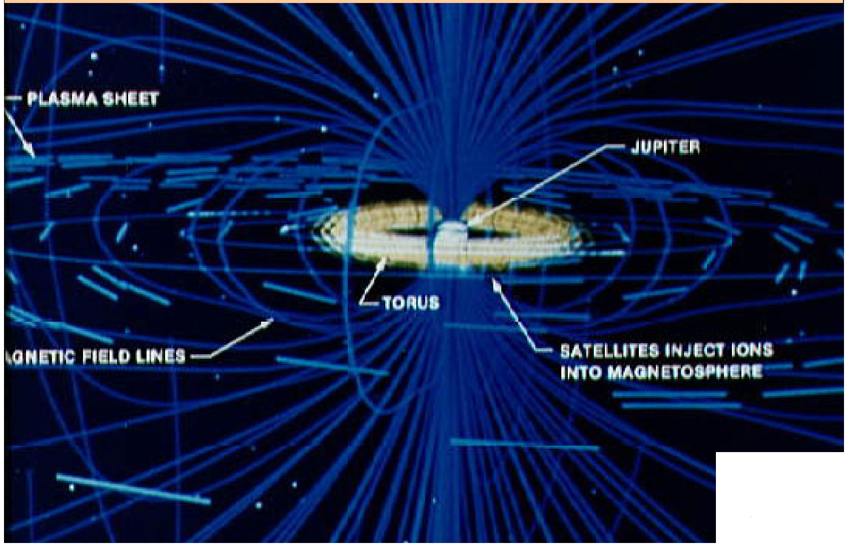
Colliding-Beam FRC
Conceptual Design Exists for Space Propulsion

- Variant of "classic" FRC.
- Invokes p-^{11}B fusion fuel.
- 51 MW_{thrust}, 33 Mg mass $\Rightarrow \alpha = 1.5$ kW/kg

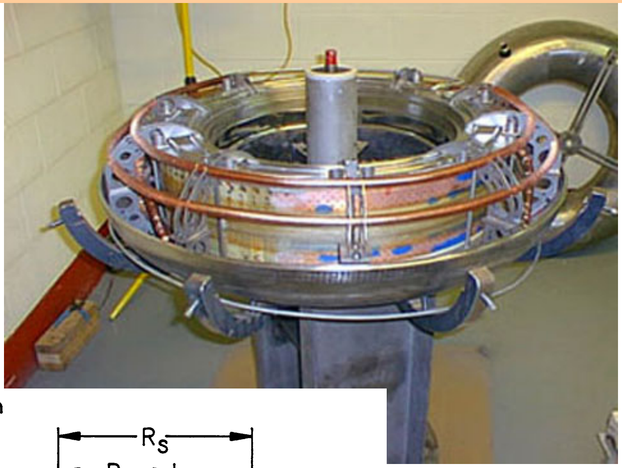


The Dipole Configuration Offers a Relatively Simple Design That an MIT/Columbia Team Is Testing

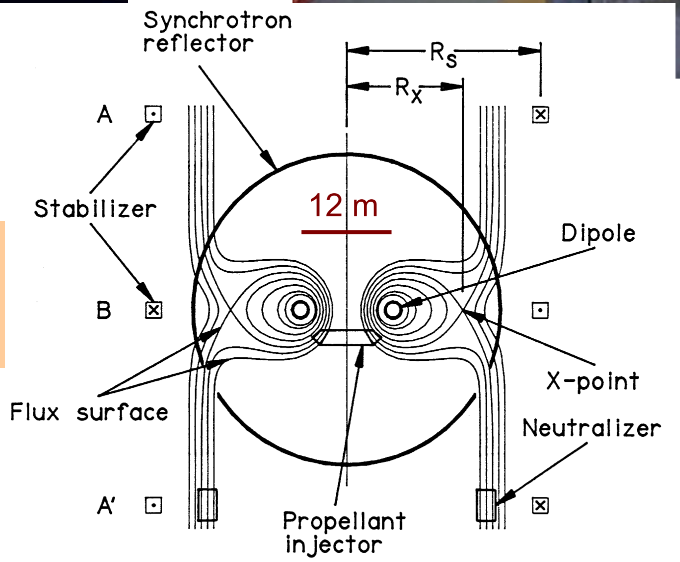
Io plasma torus around Jupiter



LDX experiment
(under construction at MIT)

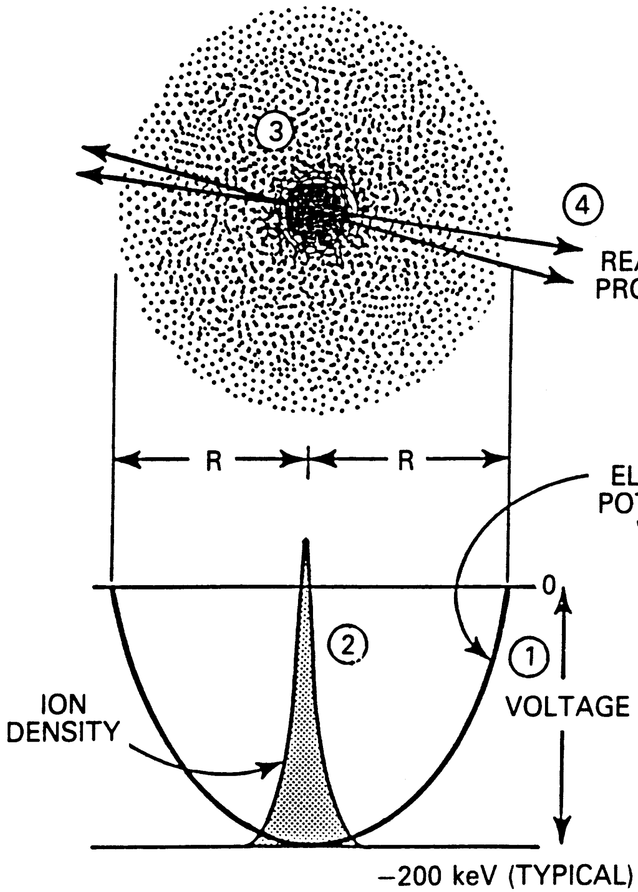


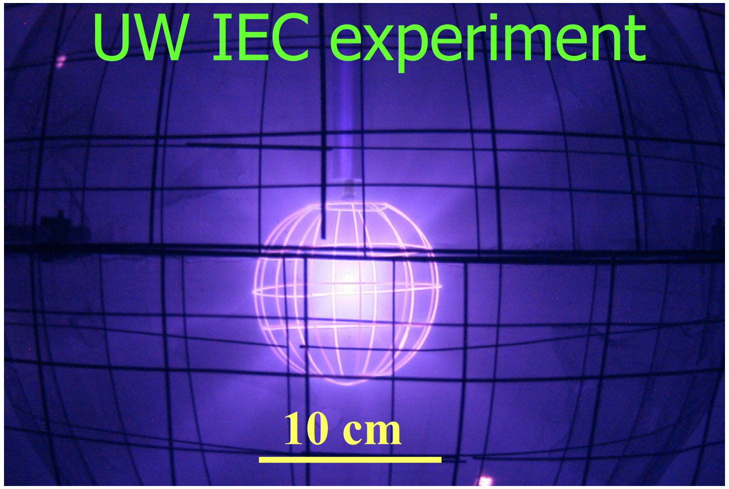
Dipole space propulsion design
(Teller, et al., 1992)

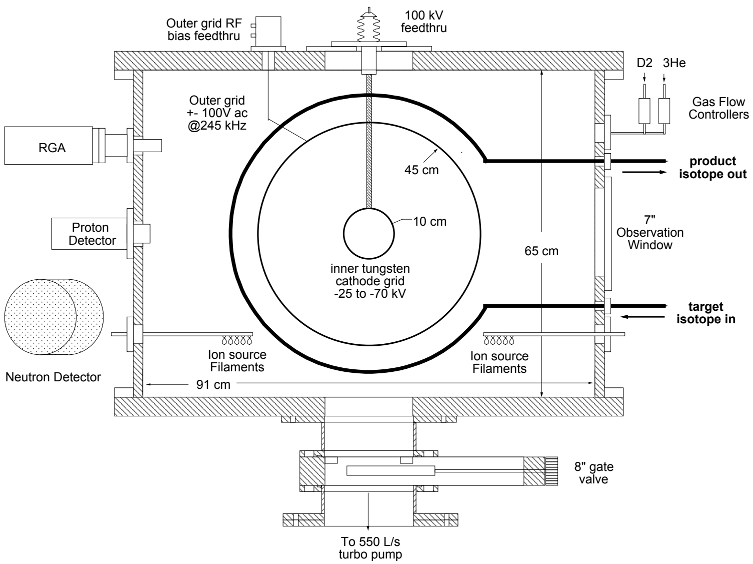


Inertial-Electrostatic Confinement (IEC) May Be Attractive for Space Propulsion

- Key principle: spherical or cylindrical electrostatic focussing.

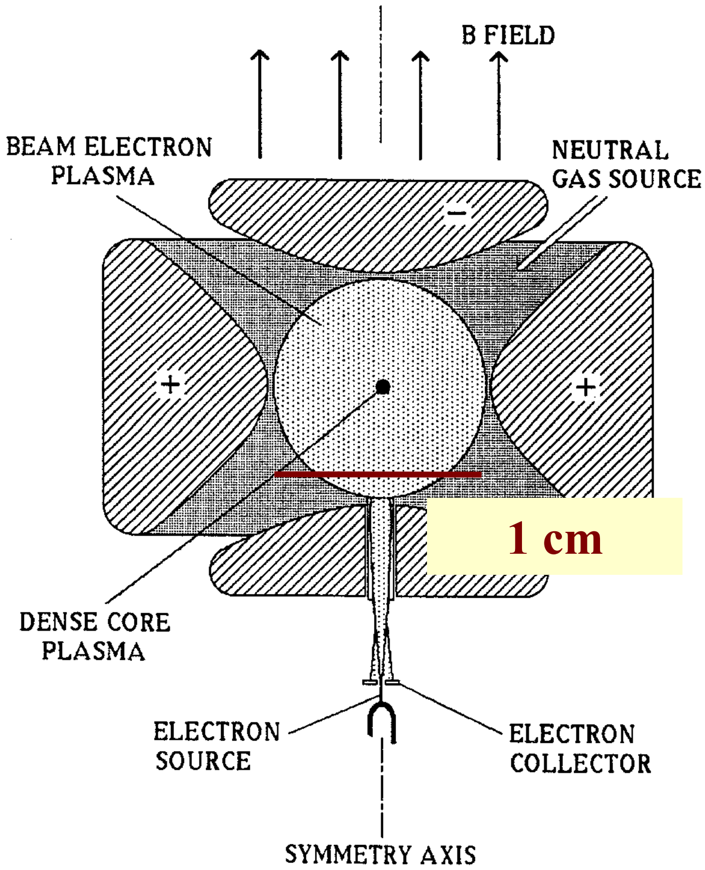




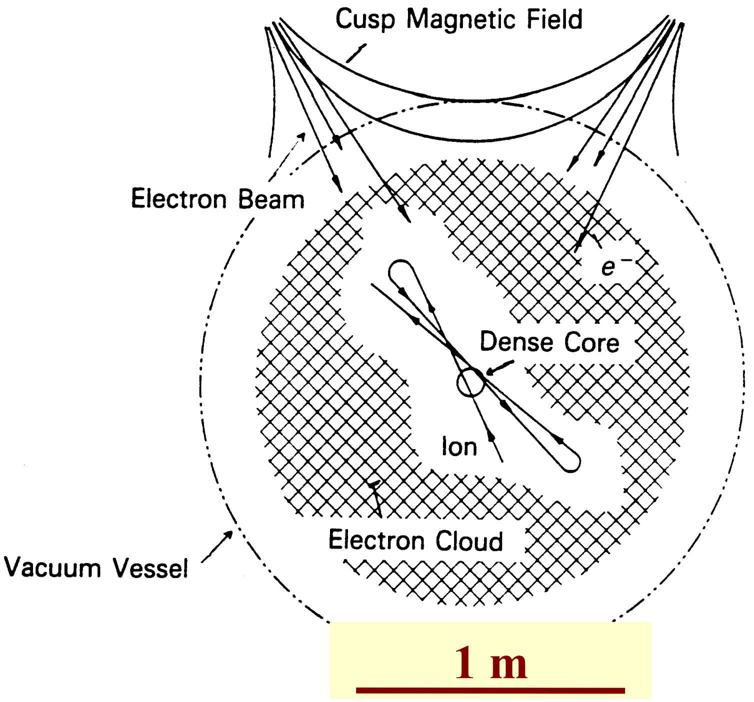


Other IEC Concepts
Potentially Attractive for Space Propulsion

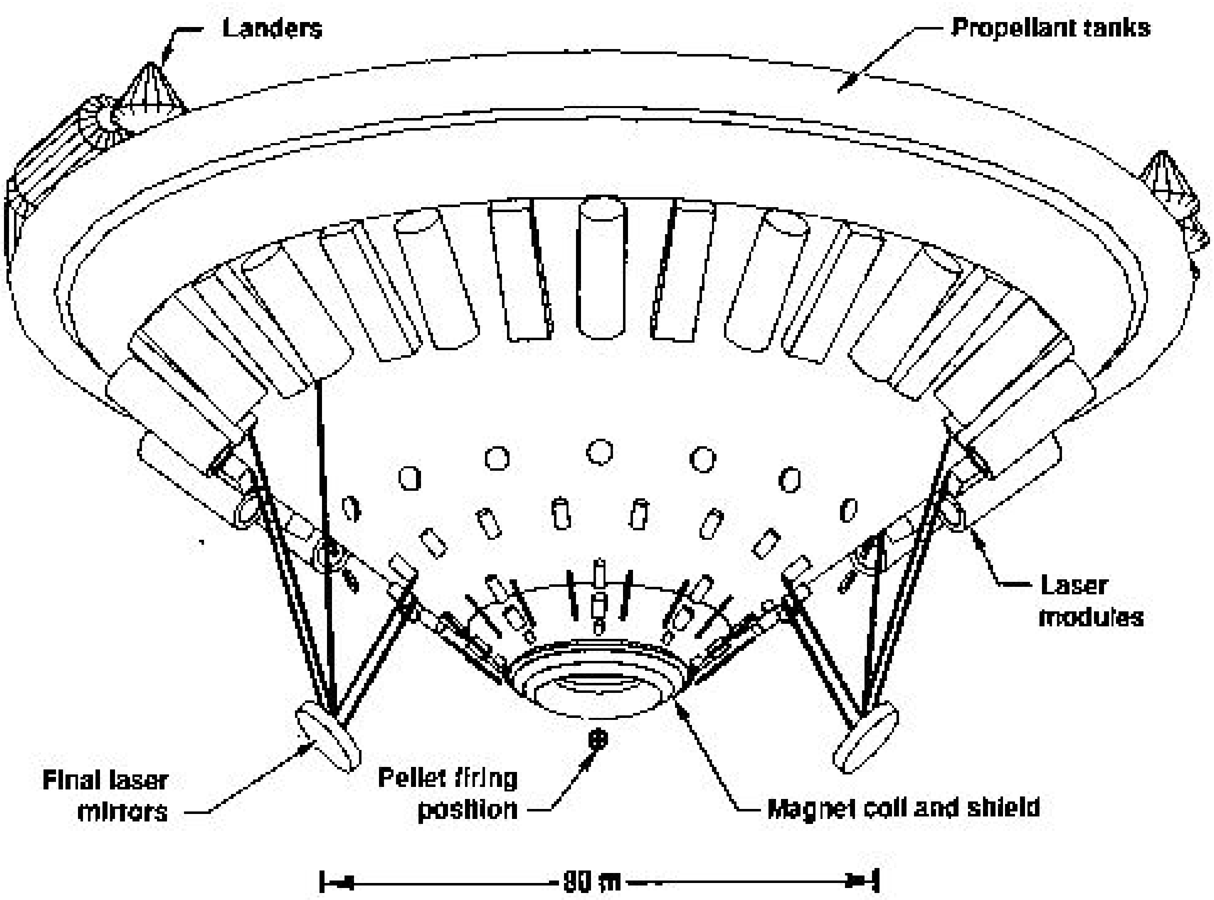
Barnes-Nebel-Turner, Penning Trap



Bussard, *Polywell*



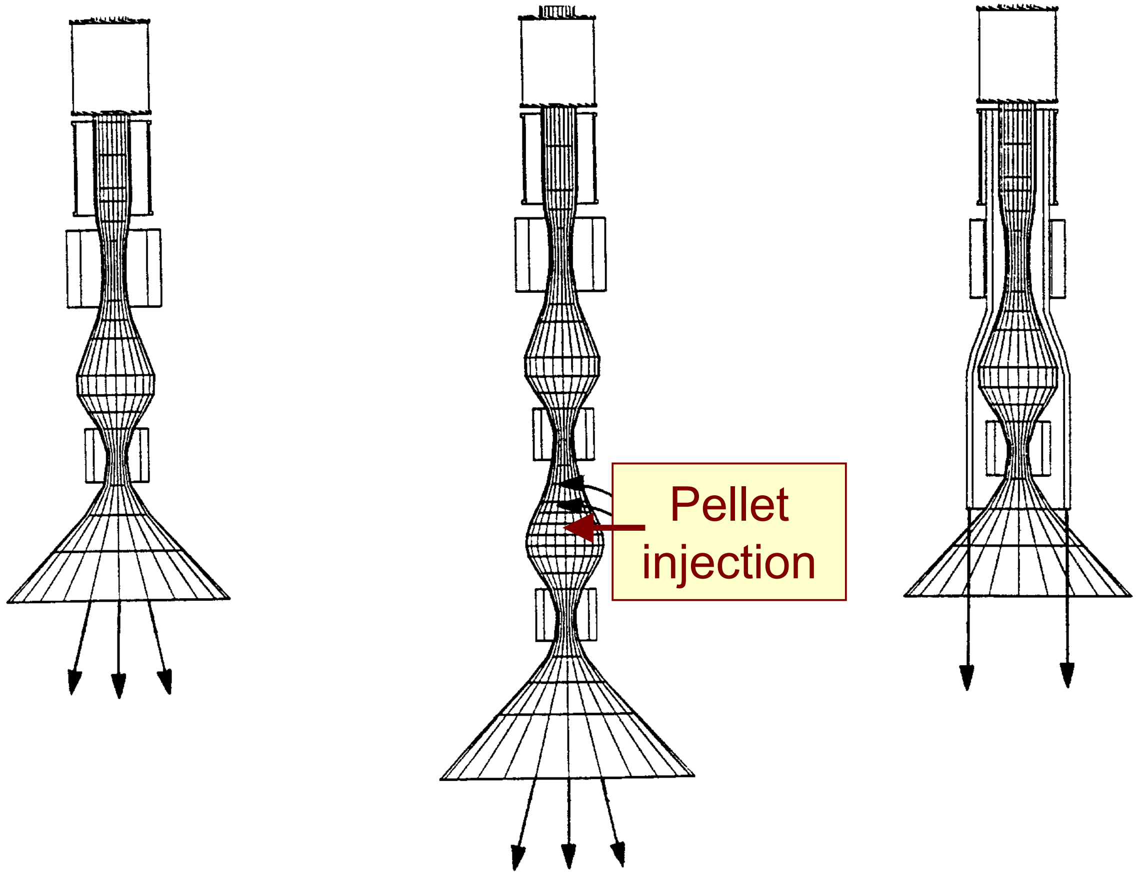
VISTA: Fusion Propulsion Using Inertial-Confinement Fusion (ICF)



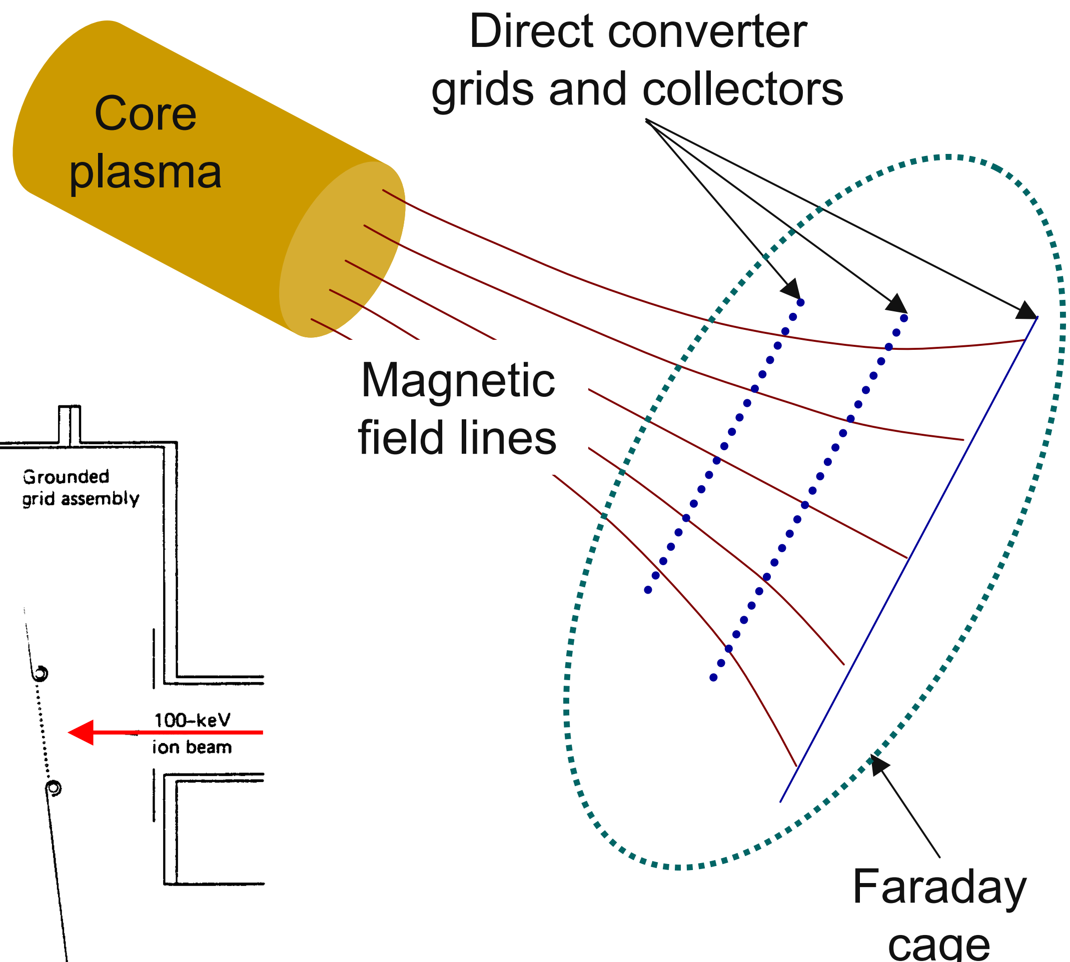
Charles Orth, et al., "The VISTA Spacecraft--Advantages of ICF for Interplanetary Fusion Propulsion Applications," IEEE 12th SOFE (1987).

D-^{3}He Fusion Propulsion Could Provide Flexible Thrust Modes

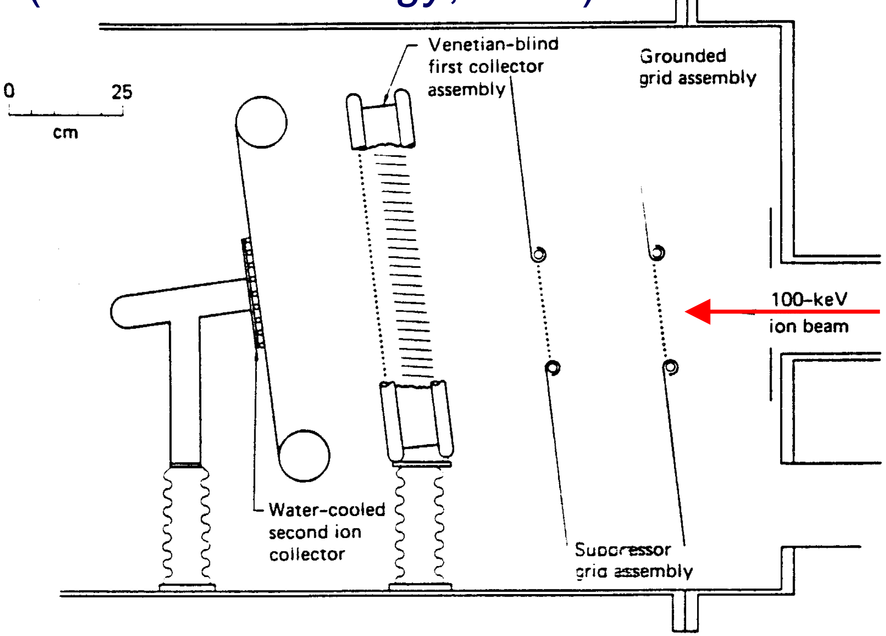
Fuel plasma exhaust | **Mass-augmented exhaust** | **Thermal exhaust**



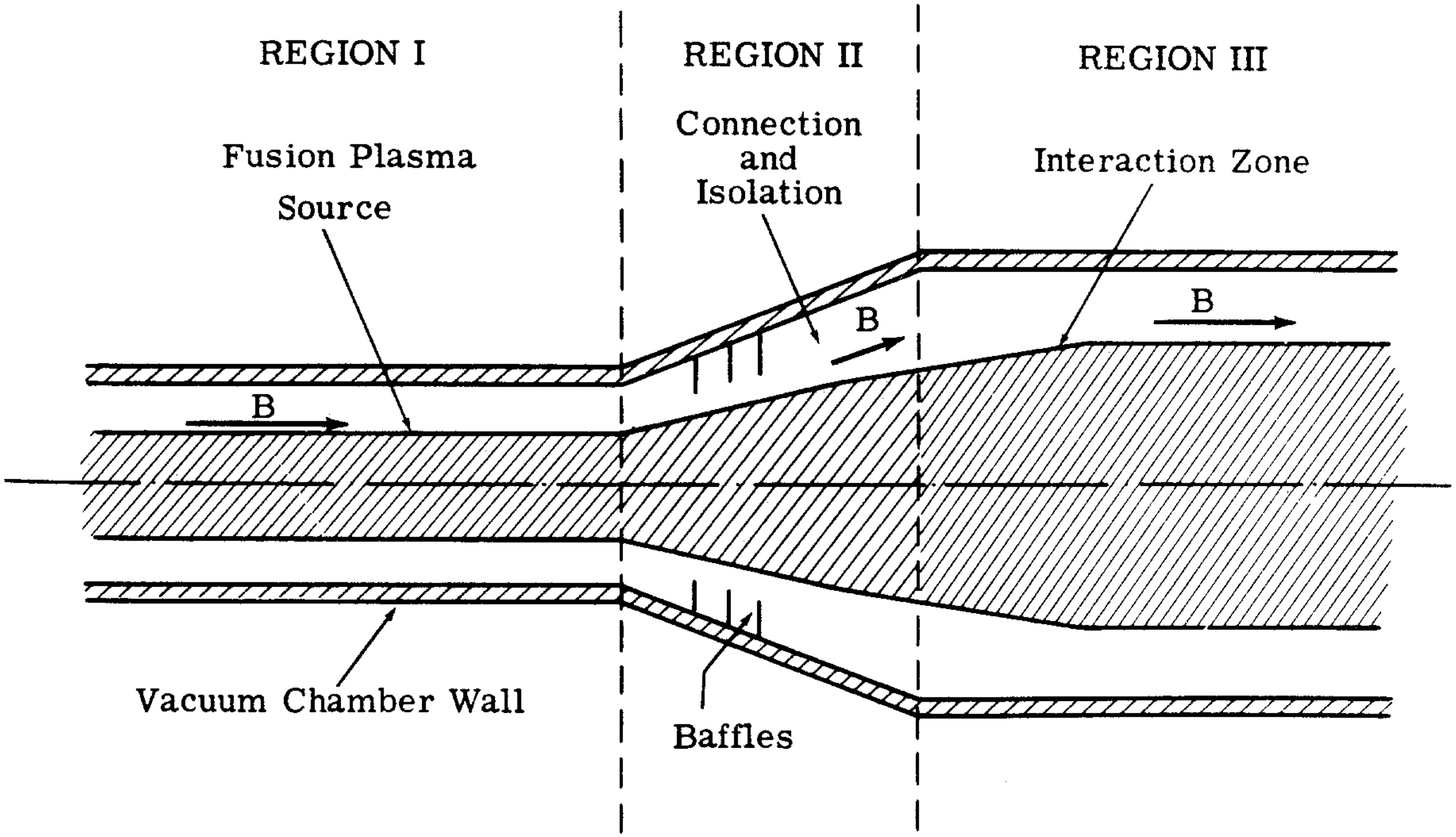
Direct Conversion to Electricity Could Take Advantage of the Natural Vacuum in Space



Barr-Moir experiment, LLNL
(*Fusion Technology*, 1973)



Plasmas Provide Many Materials Processing Capabilities



- B.J. Eastlund and W.C. Gough, "The Fusion Torch--Closing the Cycle from Use to Reuse," WASH-1132 (US AEC, 1969).

Summary

- D-^{3}He fusion requires continued physics progress.
- D-^{3}He engineering appears manageable.
- Several configurations appear promising for space propulsion, particularly the field-reversed configuration (FRC), magnetized-target fusion (MTF), spheromak, and spherical torus.
- Successful development of D-^{3}He fusion would provide attractive propulsion, power, and materials processing capabilities.