Fusion Propulsion

Opening the Solar System Frontier

John F Santarius

Lecture 27

Resources from Space

NEEP 533/ Geology 533 / Astronomy 533 / EMA 601

University of Wisconsin

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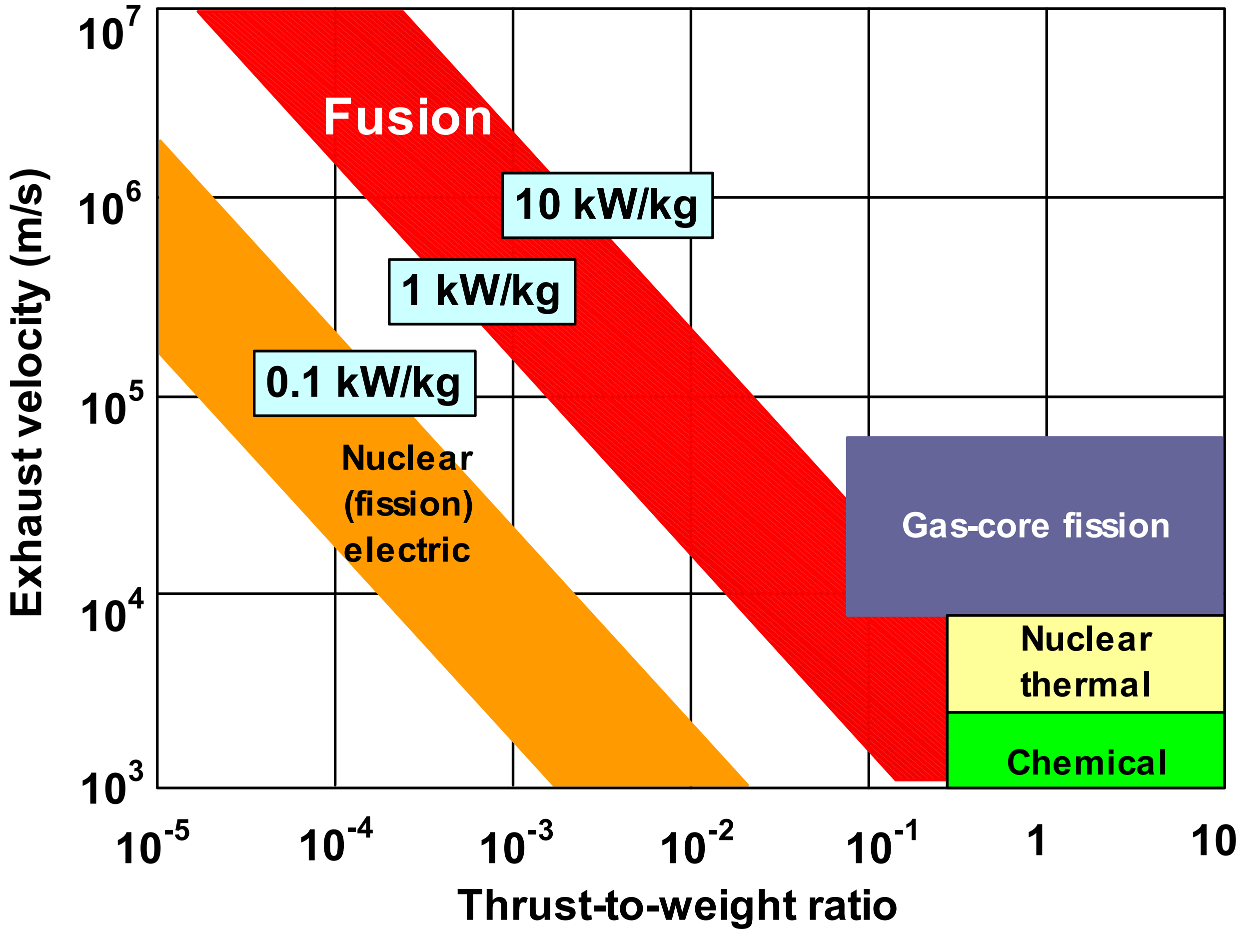
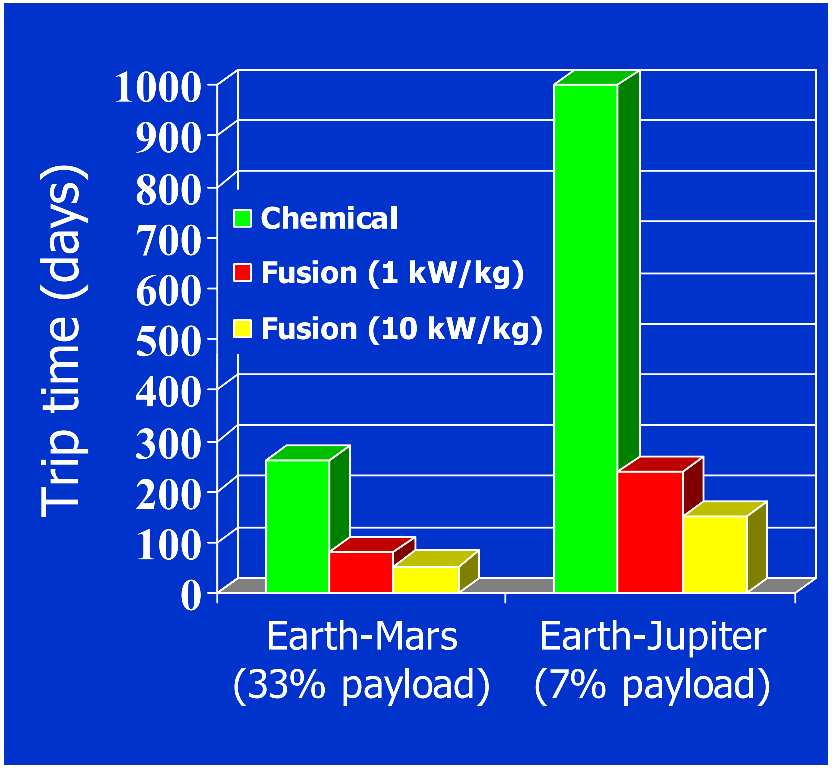
D-^{3}He Fusion Will Provide Capabilities Not Available from Other Propulsion Options



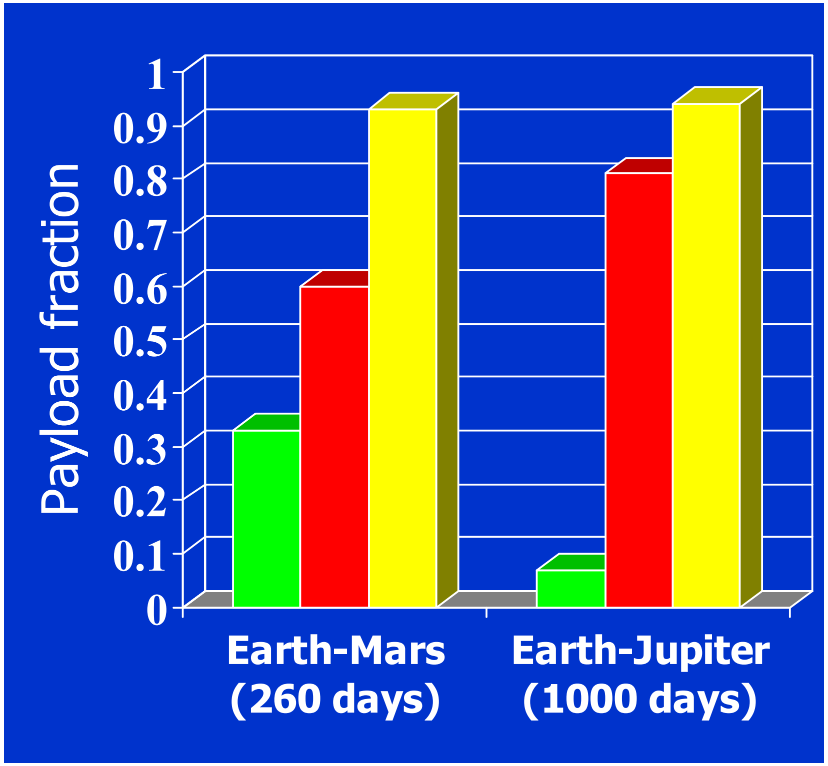
At the Predicted α=1-10 kW/kg, Fusion Propulsion Would Enable Attractive Solar-System Travel

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

Fast human transport



Efficient cargo transport



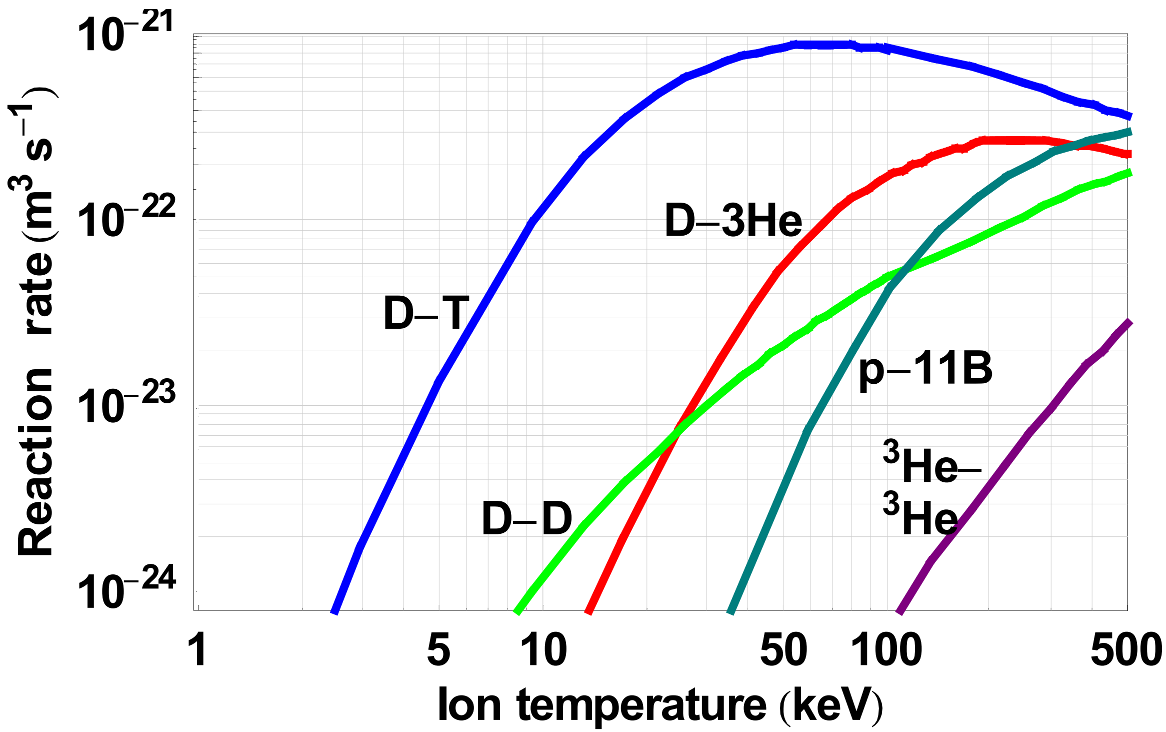
Key Fusion Fuel Cycles for Space Applications

D + ^{3}He → p (14.68 MeV) + ^{4}He (3.67 MeV)

D + T → n (14.07 MeV) + ^{4}He (3.52 MeV)

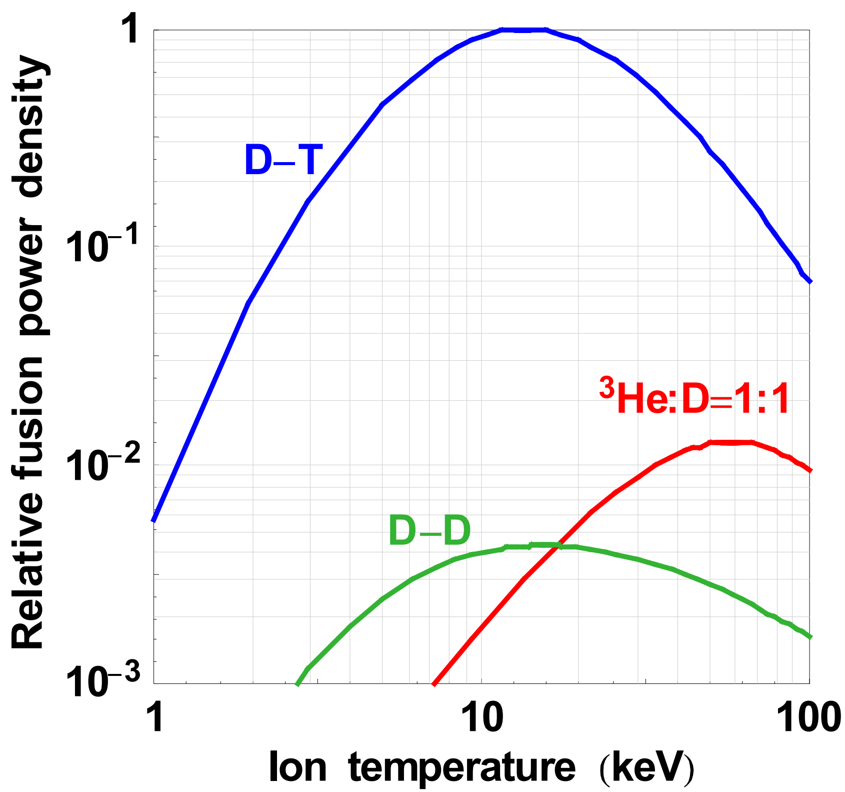
D + D → n (2.45 MeV) + ^{3}He (0.82 MeV) {50%}

→ p (3.02 MeV) + T (1.01 MeV) {50%}

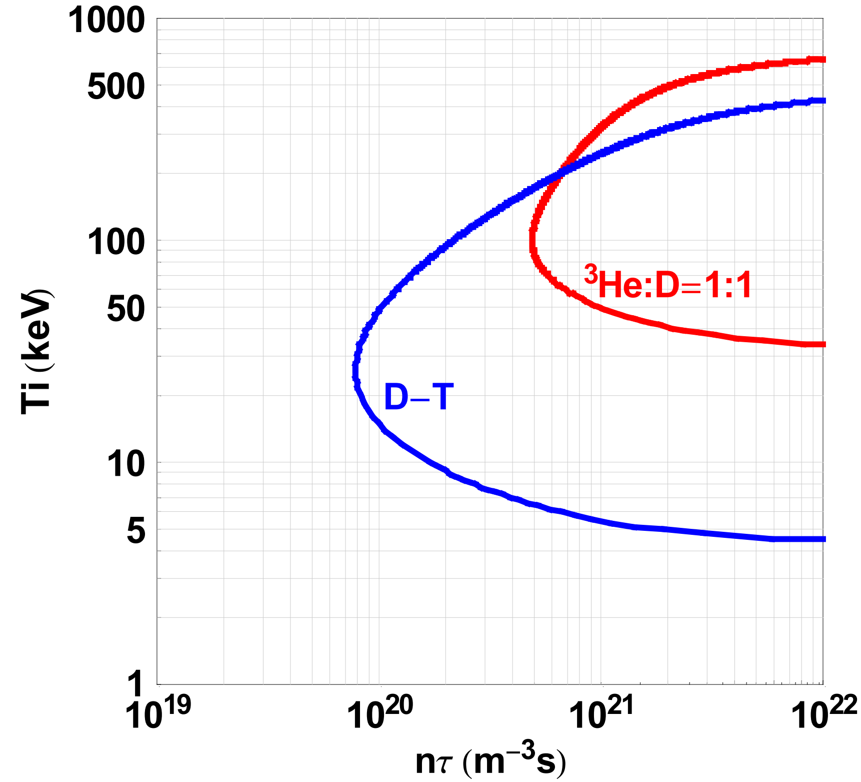


Physics Viewpoint: D-^{3}He Fuel Requires High $\beta^\dagger$, $n\tau$, and T

Power density



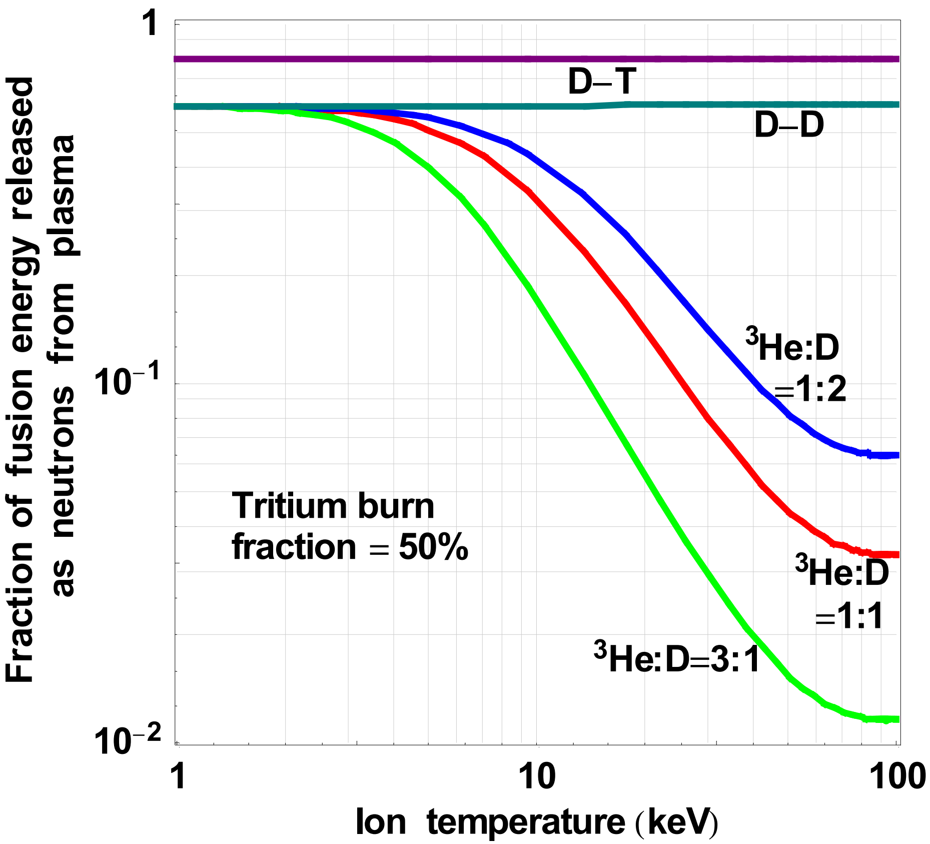
Confinement



† β = plasma pressure/magnetic field pressure.

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

- Many configurations can increase fusion core B fields, gaining power density due to the $\beta^2 B^4$ scaling.
- Reduced neutron flux allows
  - ➢ Smaller radiation shields
  - ➢ Smaller magnets
- Increased charged-particle flux allows direct energy conversion to thrust or electricity



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

- Prediction based on reasonably detailed magnetic fusion rocket studies performed during the past fifteen years.
- Rationale for this performance supported by J.F. Santarius and B.G. Logan, "Generic Magnetic Fusion Rocket," *Journal of Propulsion and Power* **14**, 519 (1998).
- 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.

Key Features of the Generic Fusion Rocket Model

- Cylindrical geometry
- Main contributors to mass: radiation shield, 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
- Magnet He refrigerators require 1000 $kg/kW_{rejected}$
- Low-mass radiation shield (LiH with 10% Al structure)
  - Ten-fold magnet nuclear heating reduction=0.31 m of shield
- Magnet mass calculated by virial theorem and by winding-pack current density limit (50 MA/m^2); larger value used

Recent Conceptual Designs of Magnetic Fusion Reactors for Space Propulsion Calculate Very Attractive Specific Powers

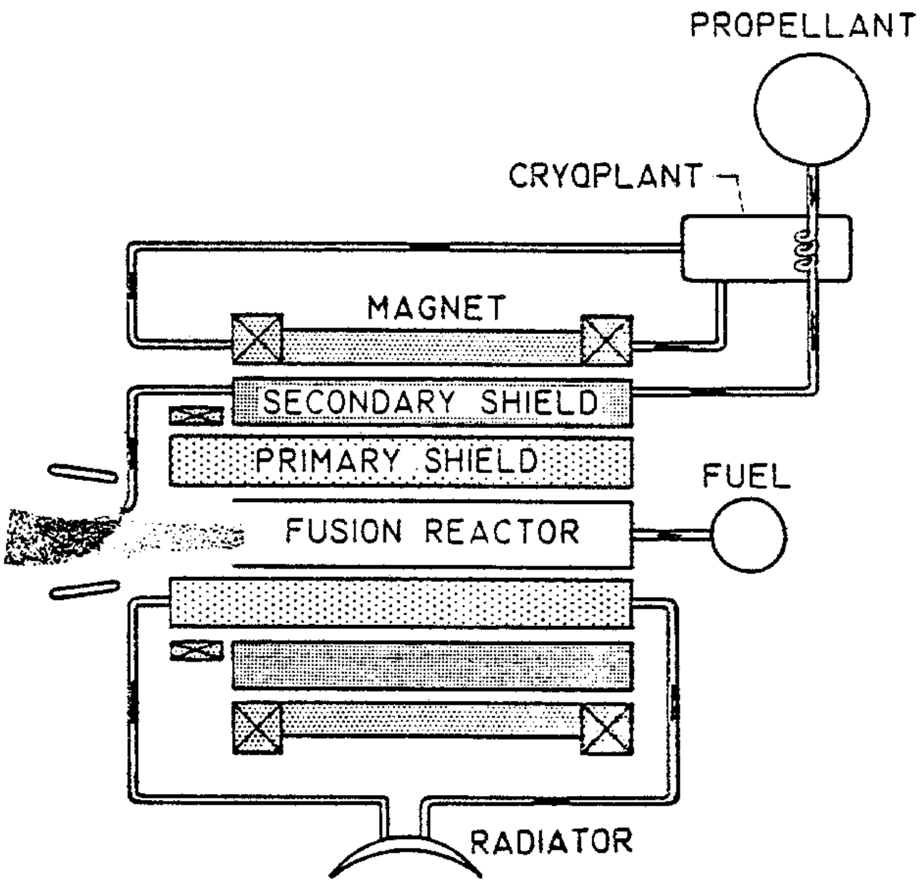
First Author	Year	Configuration	Specific Power (kW/kg)
Borowski	1987	Spheromak	10.5
Borowski	1987	Spherical torus	5.8
Santarius	1988	Tandem mirror	1.2
Bussard	1990	Riggatron	3.9
Teller	1991	Dipole	1.0
Nakashima	1994	Field-reversed configuration	1.0
Williams	1999	Spherical torus	4.9
Thio	1999	Magnetized-target fusion	600
Emrich	2000	Gasdynamic mirror	130
Wessel	2000	Colliding-beam FRC	2.3

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

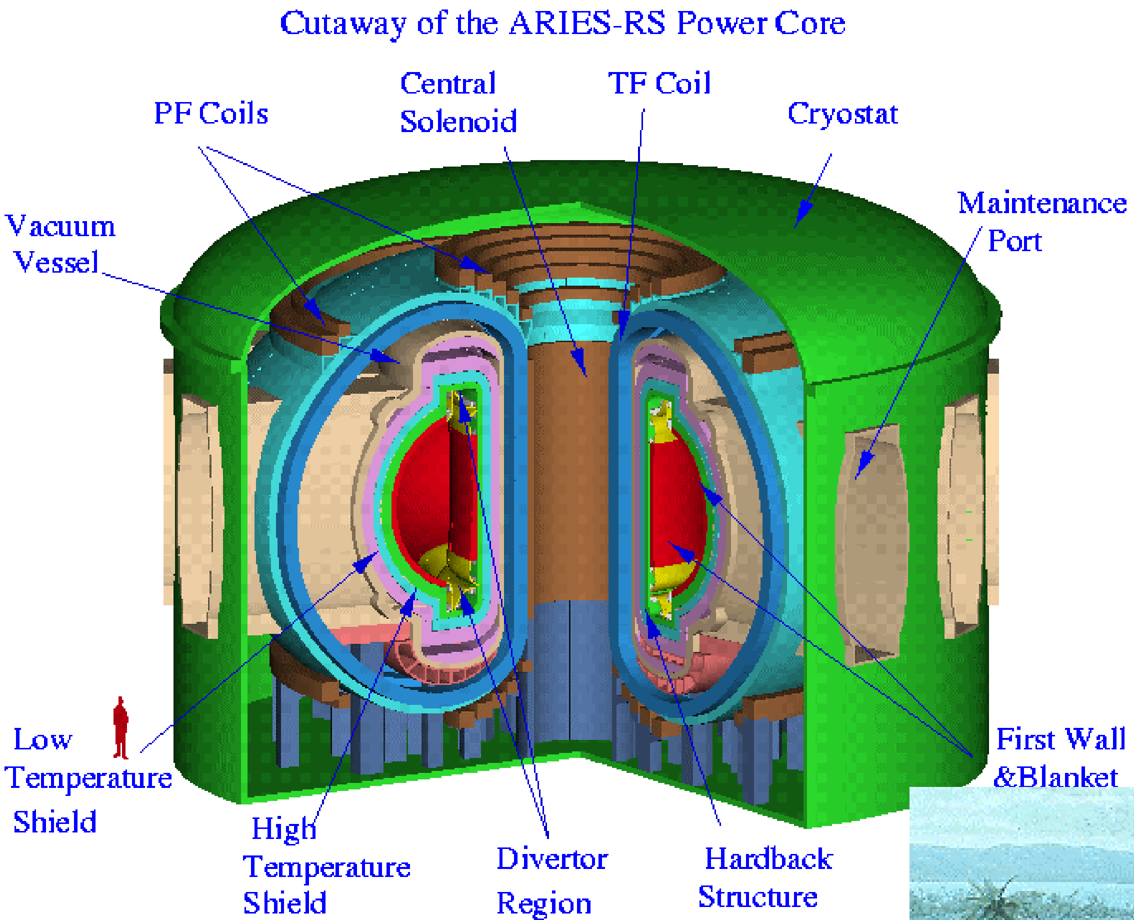
G.W. Englert,
NASA Glenn Research Center
New Scientist (1962)

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

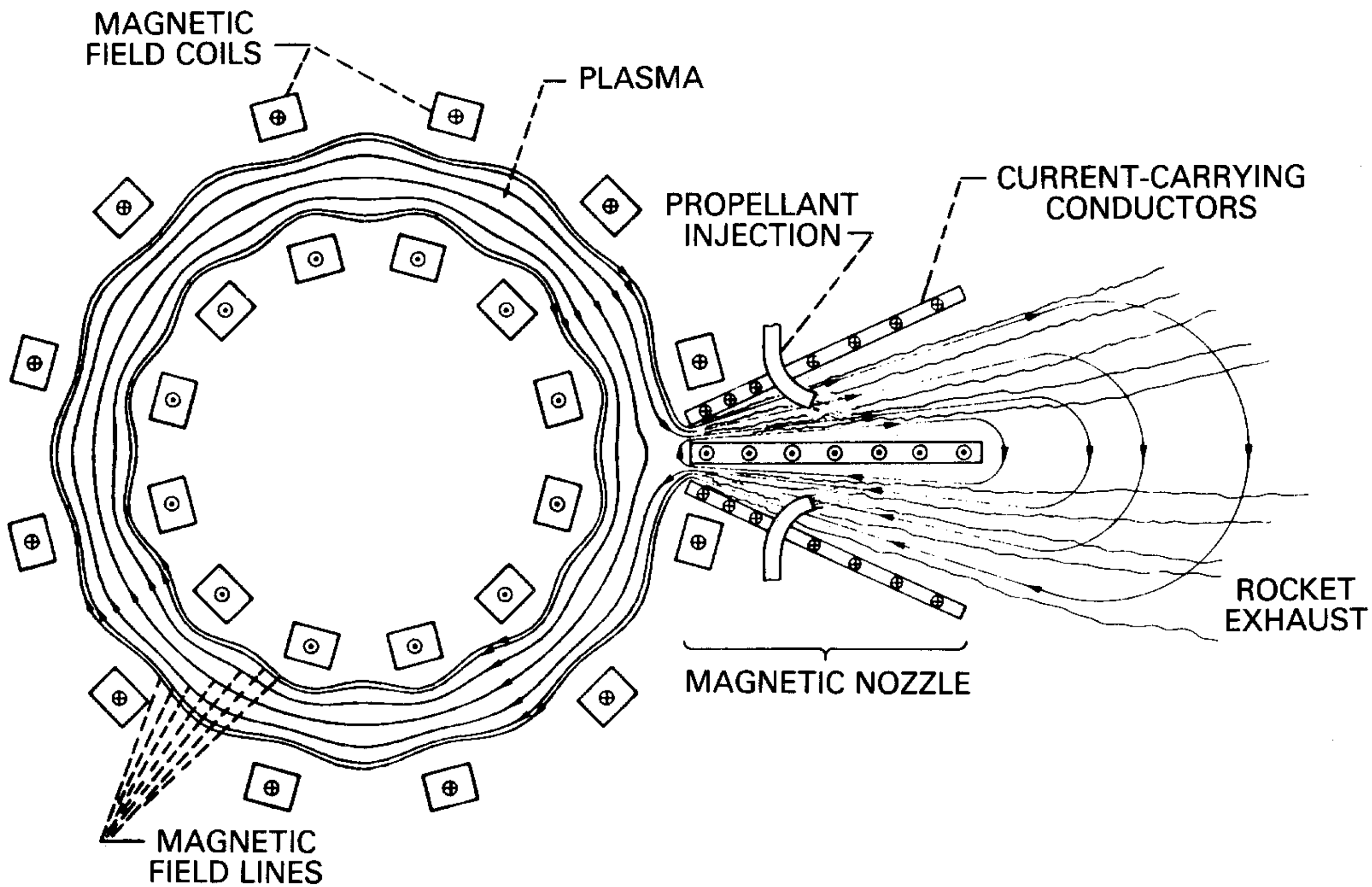
The application of superconducting magnets and a mixture of deuterium and helium-3 as fuel appears to be the most promising arrangement."



Conventional Tokamaks Have Large Mass



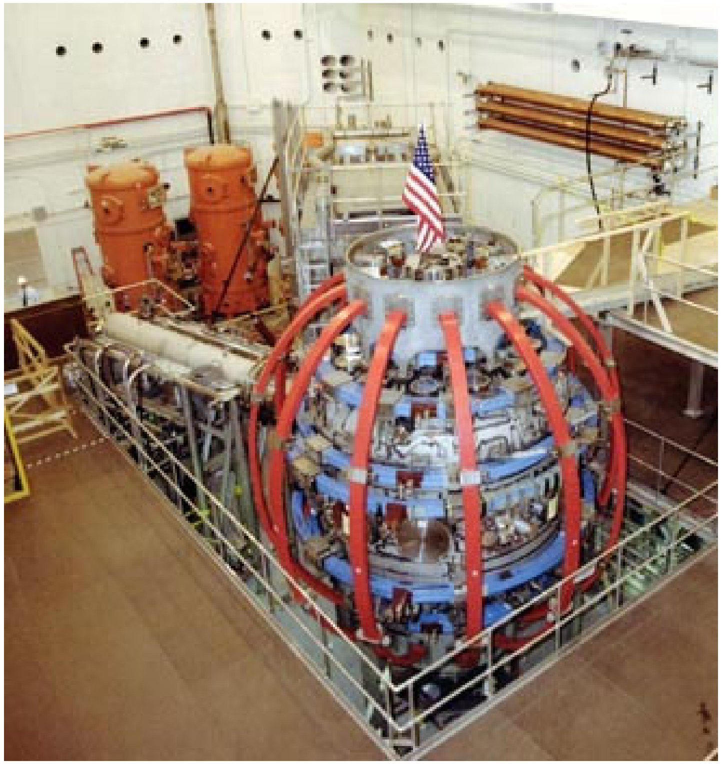
EFBT Toroidal Fusion Rocket
J. Reece Roth, NASA Lewis, 1972



Spherical Torus Space Propulsion

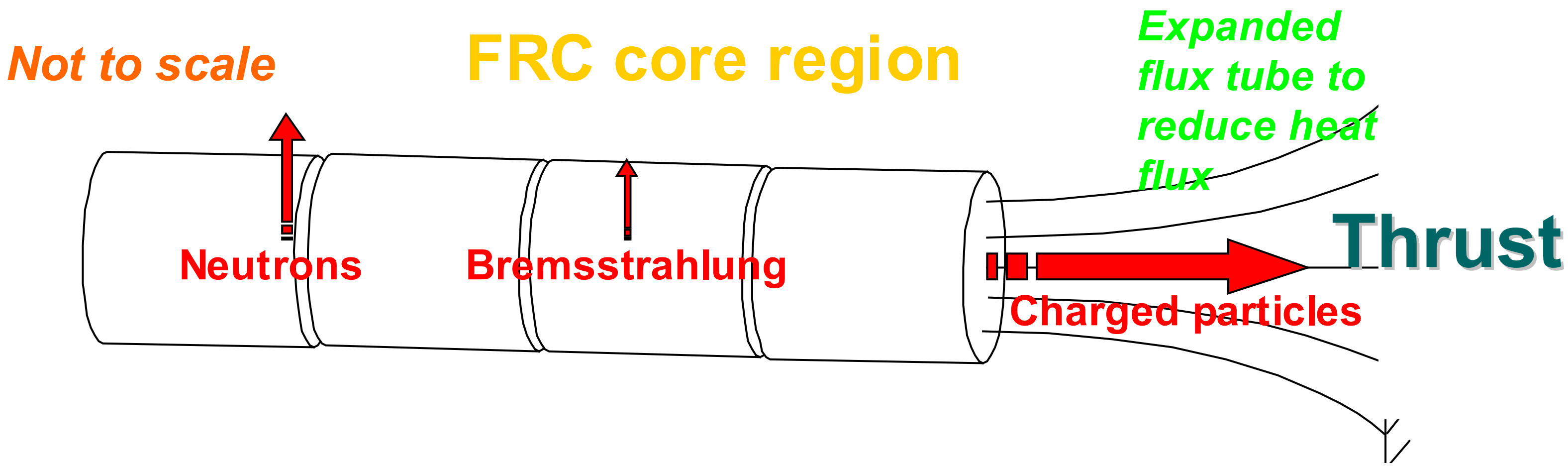
- ST's give high β, implying high power density.
- Crucial problems are recirculating power and providing thrust.
- Martin Peng has suggested helicity *ejection*, and the concept will be tried on NSTX.

Princeton Plasma Physics Lab NSTX experiment



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 would be expanded in end chamber to reduce heat and particle fluxes, so charged-particle transport power only slightly impacts the first wall.

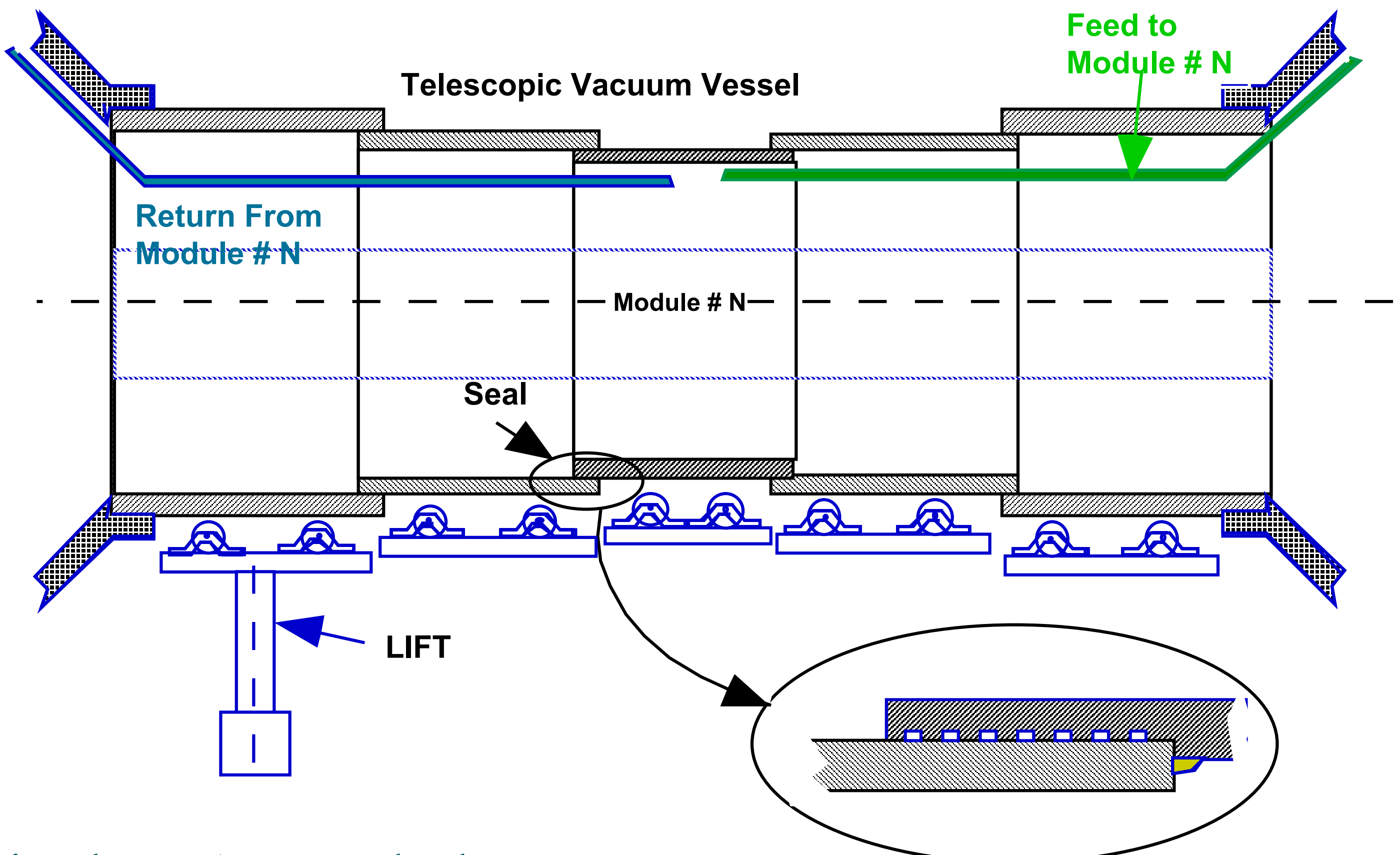


Linear Geometry Greatly Facilitates Engineering

- 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 would increase efficiency.

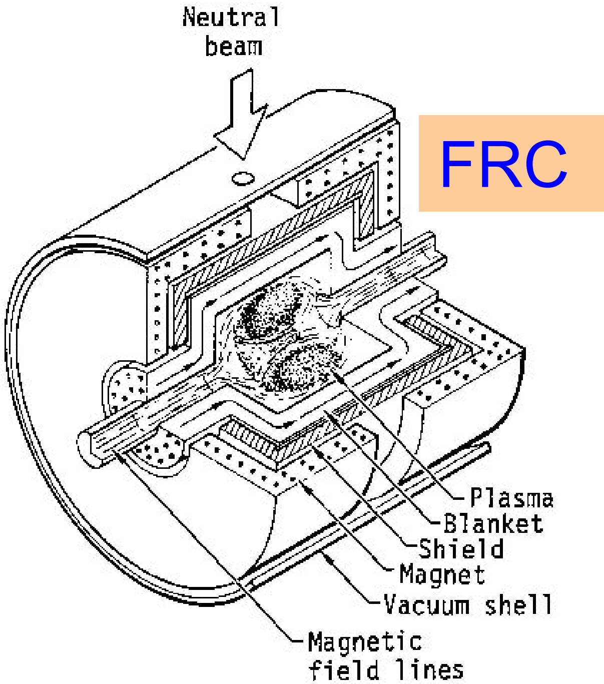
Radioactivity Will Most Likely Lead to a Requirement for Remote Maintenance

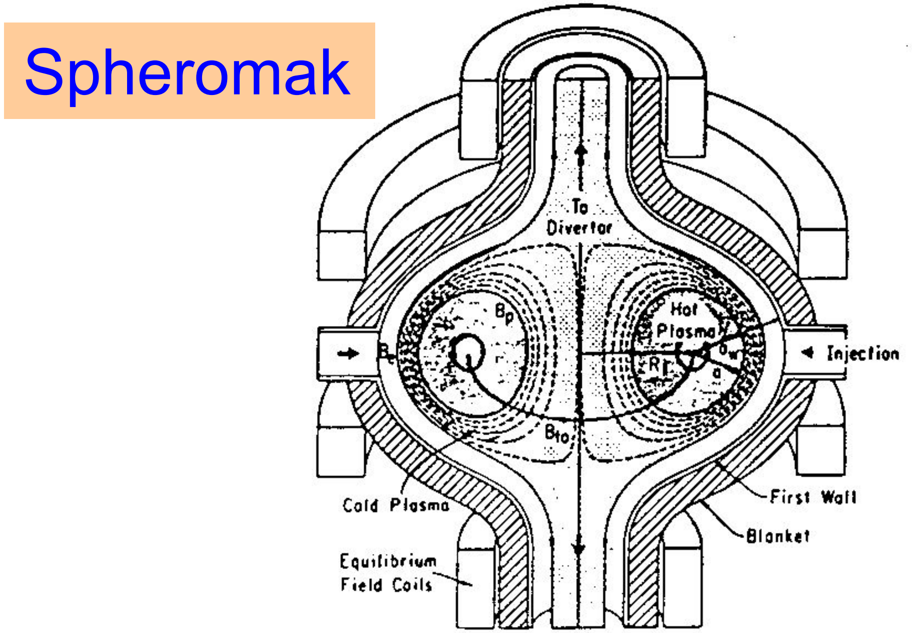
Maintenance Scheme for a Terrestrial-Electric FRC Using a Telescopic Vacuum Vessel

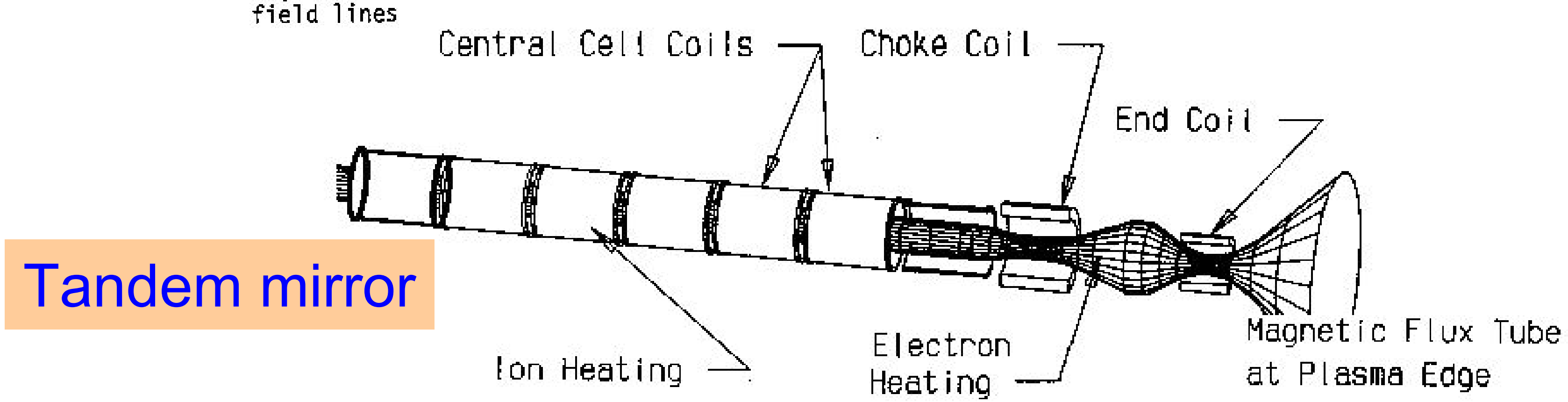


- Design by E.A. Mogahed

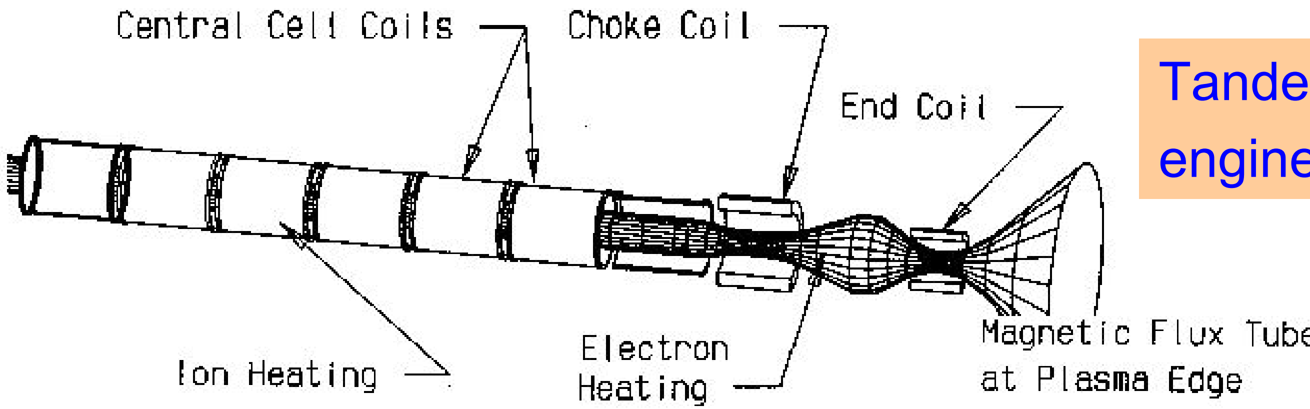
Several Concepts with Linear External Magnetic Fields Have Been Investigated for Space Propulsion







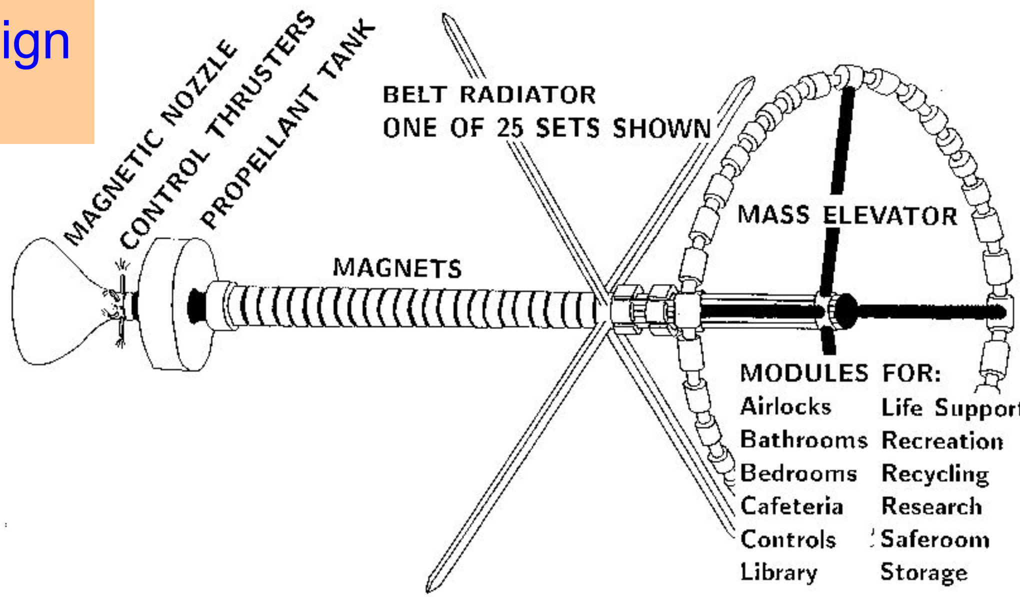
D-^{3}He Space-Propulsion Tandem Mirror



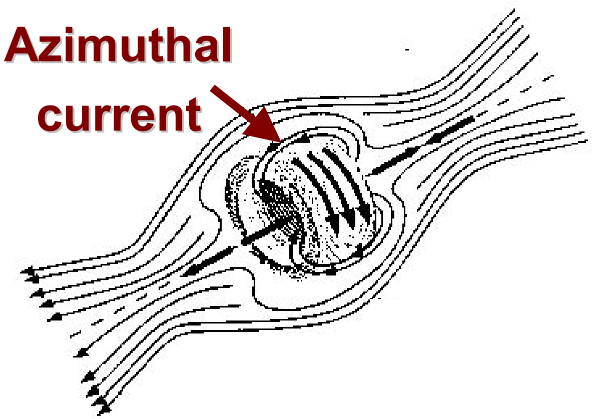
Tandem mirror engine

Tandem mirror rocket design by UW EMA 569 students

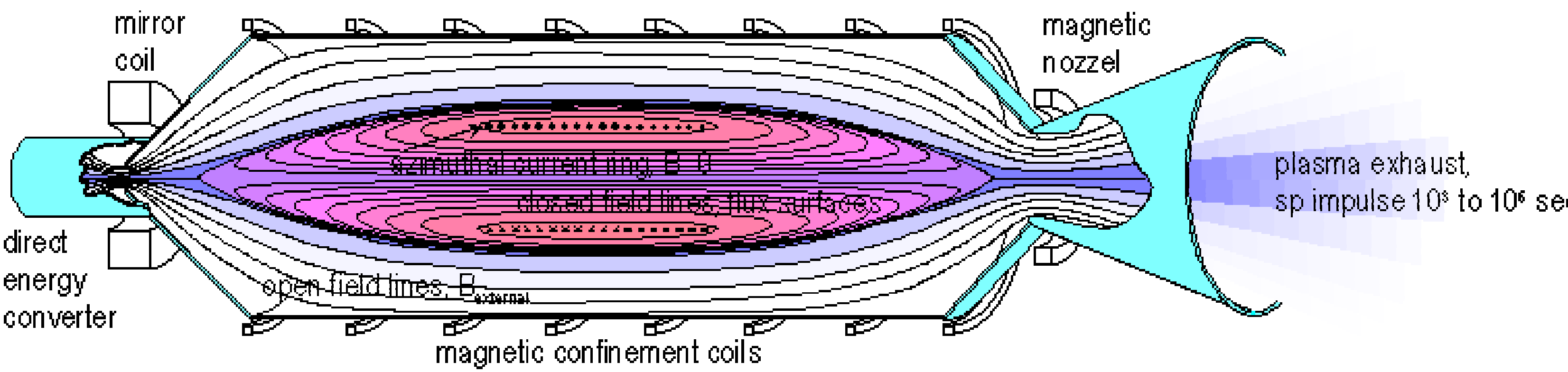
Specific power	1.2 kW/kg
Thrust power	1500 MW
Length	113 m
Ave. outer radius	1 m
Core B field	6.4 T



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



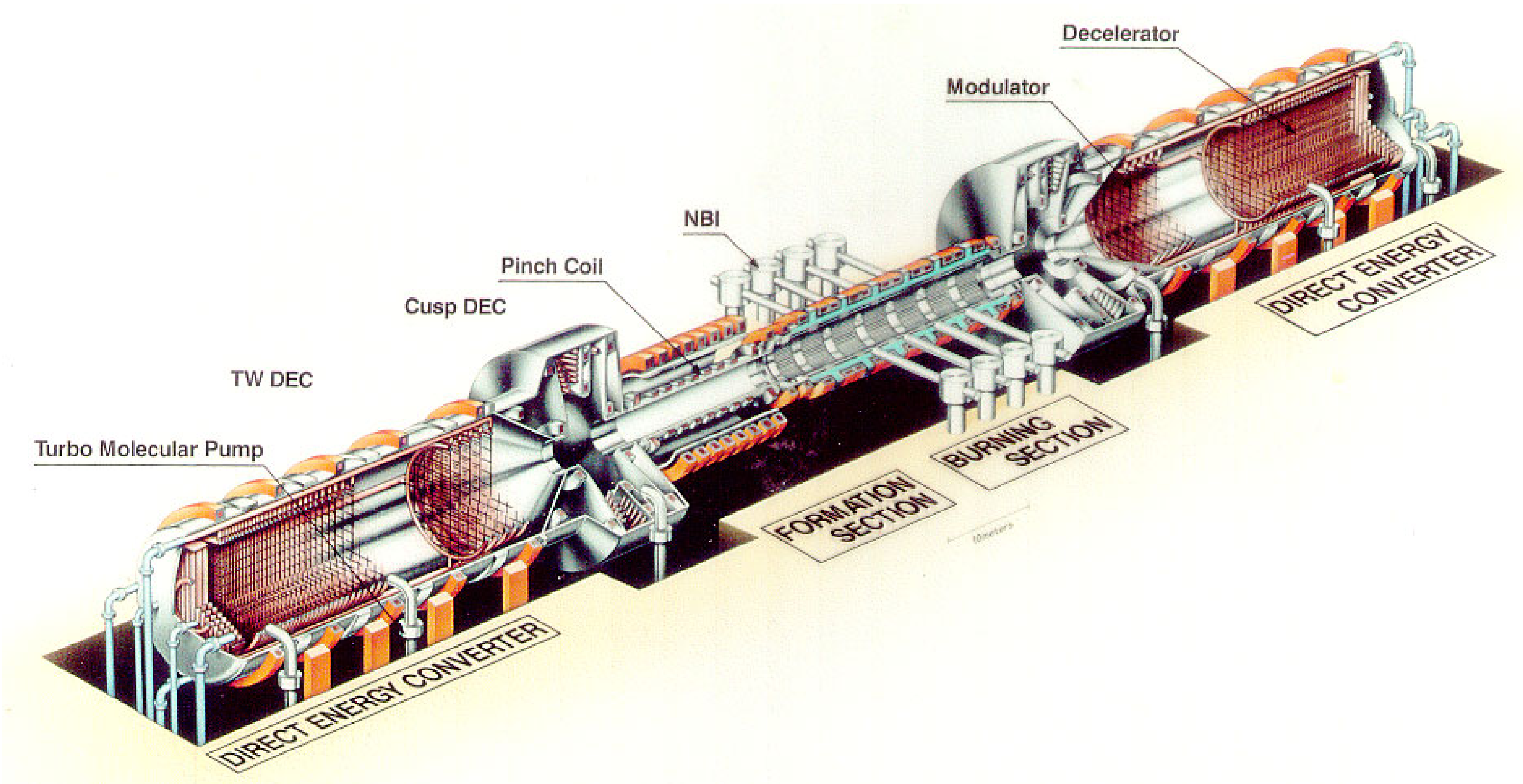
- High $\beta \equiv P_{plasma}/P_{B\text{-field}}$
- Linear external B field
- Cylindrical geometry
- RMF current drive



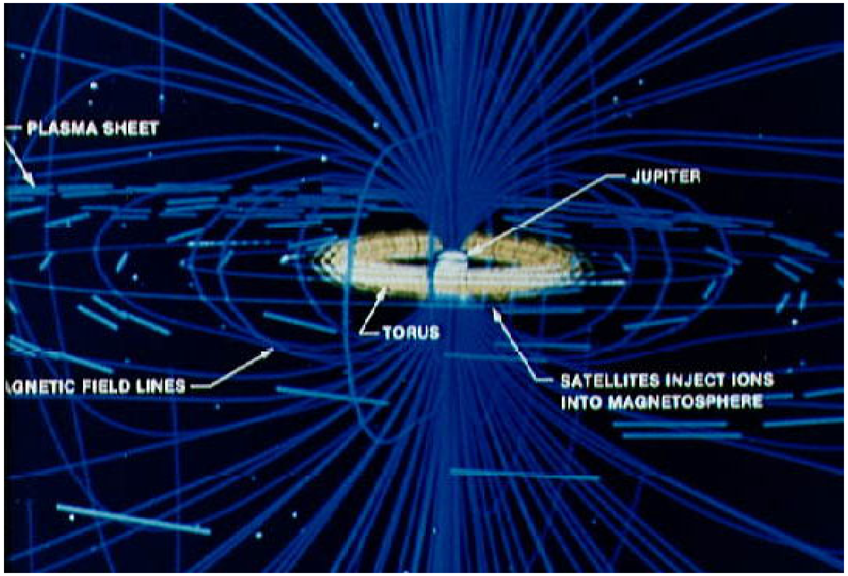
FRC as Power Source and Ion Engine for High Energy Space Missions

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)

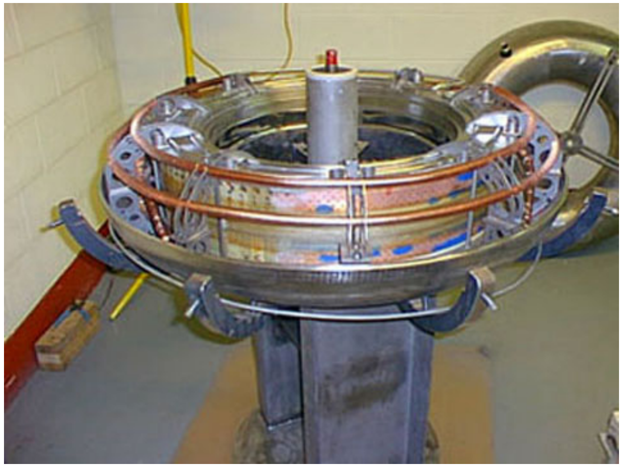


The Dipole Configuration Offers a Relatively Simple Design That an MIT/Columbia Team Is Testing



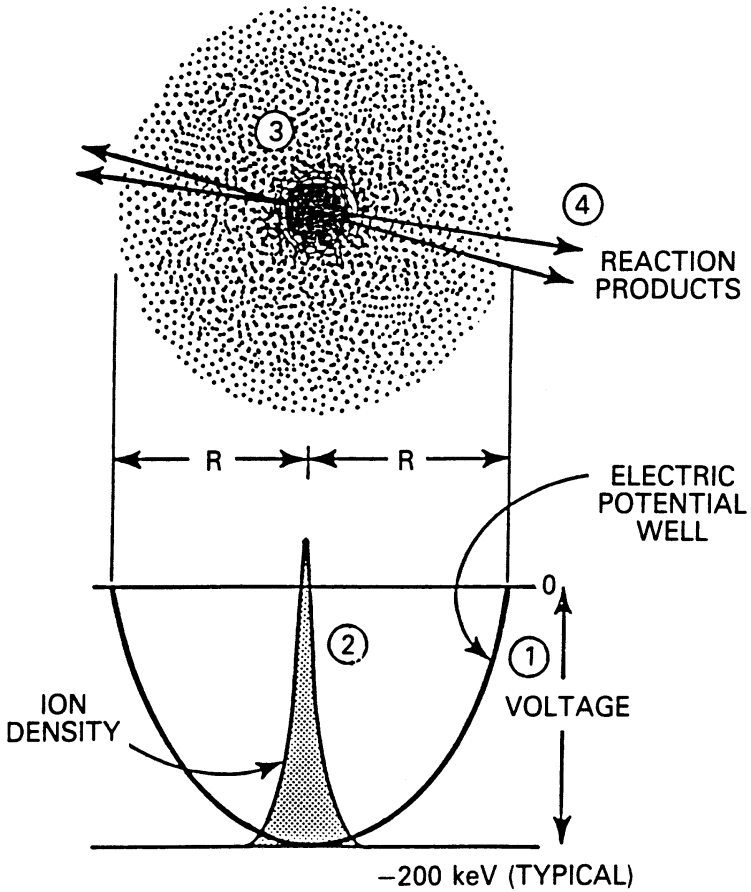
Io plasma torus around Jupiter

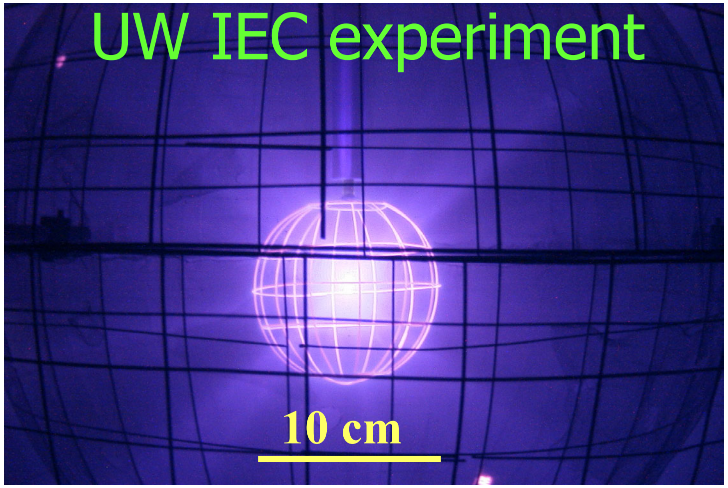
LDX experiment
(under construction at MIT)

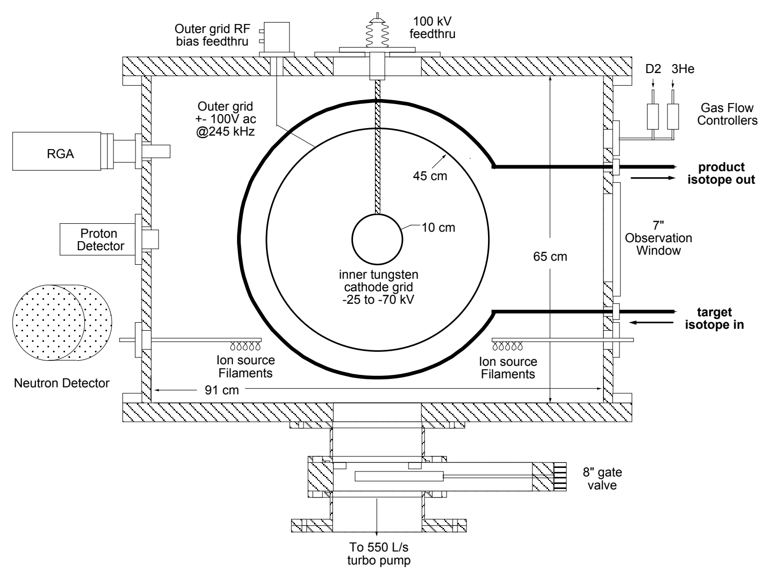


Inertial-Electrostatic Confinement (IEC) May Be Attractive for Space Propulsion

- Key principle: spherical or cylindrical electrostatic focussing.

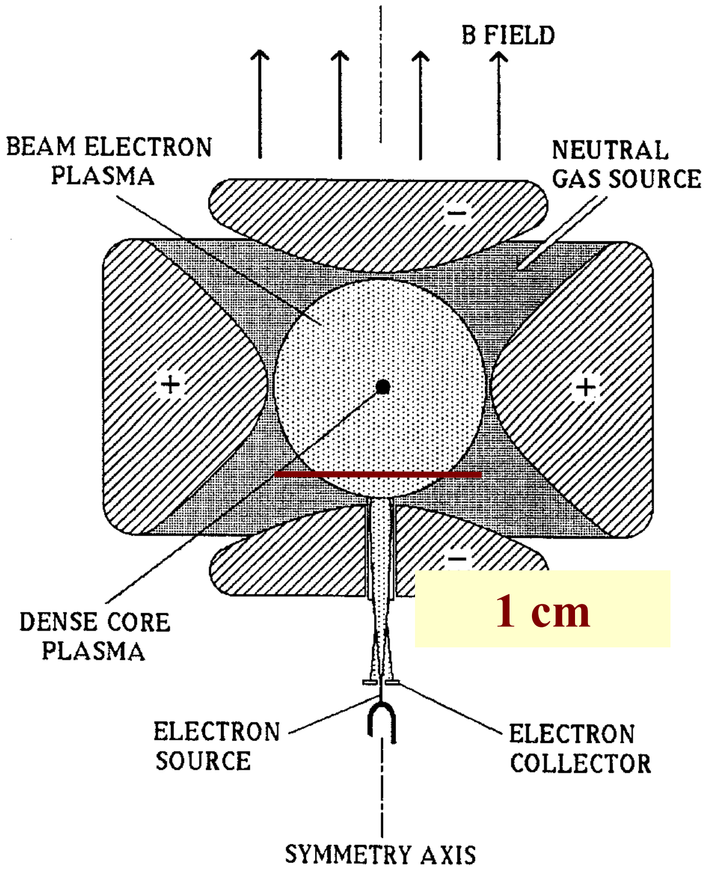




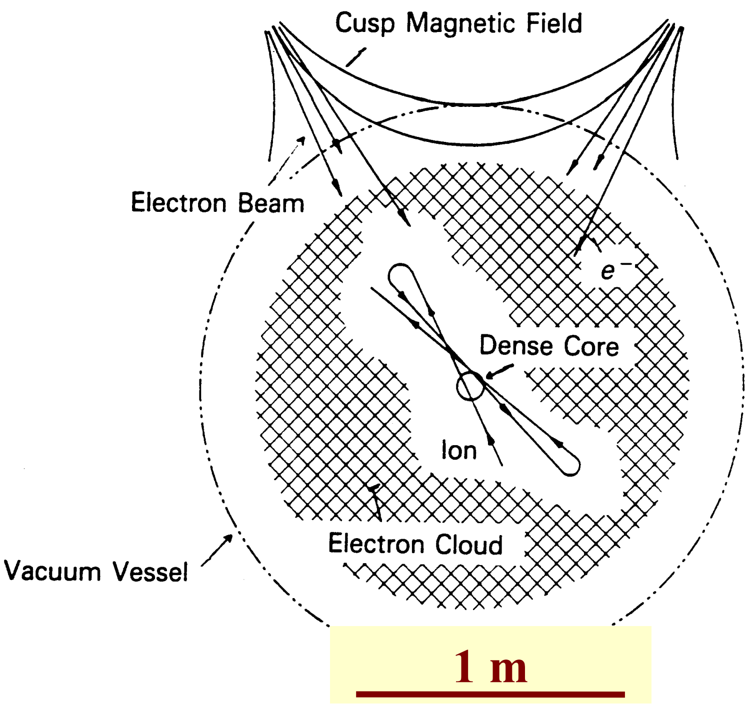


Inertial-Electrostatic Confinement (IEC) May Be Attractive for Space Propulsion

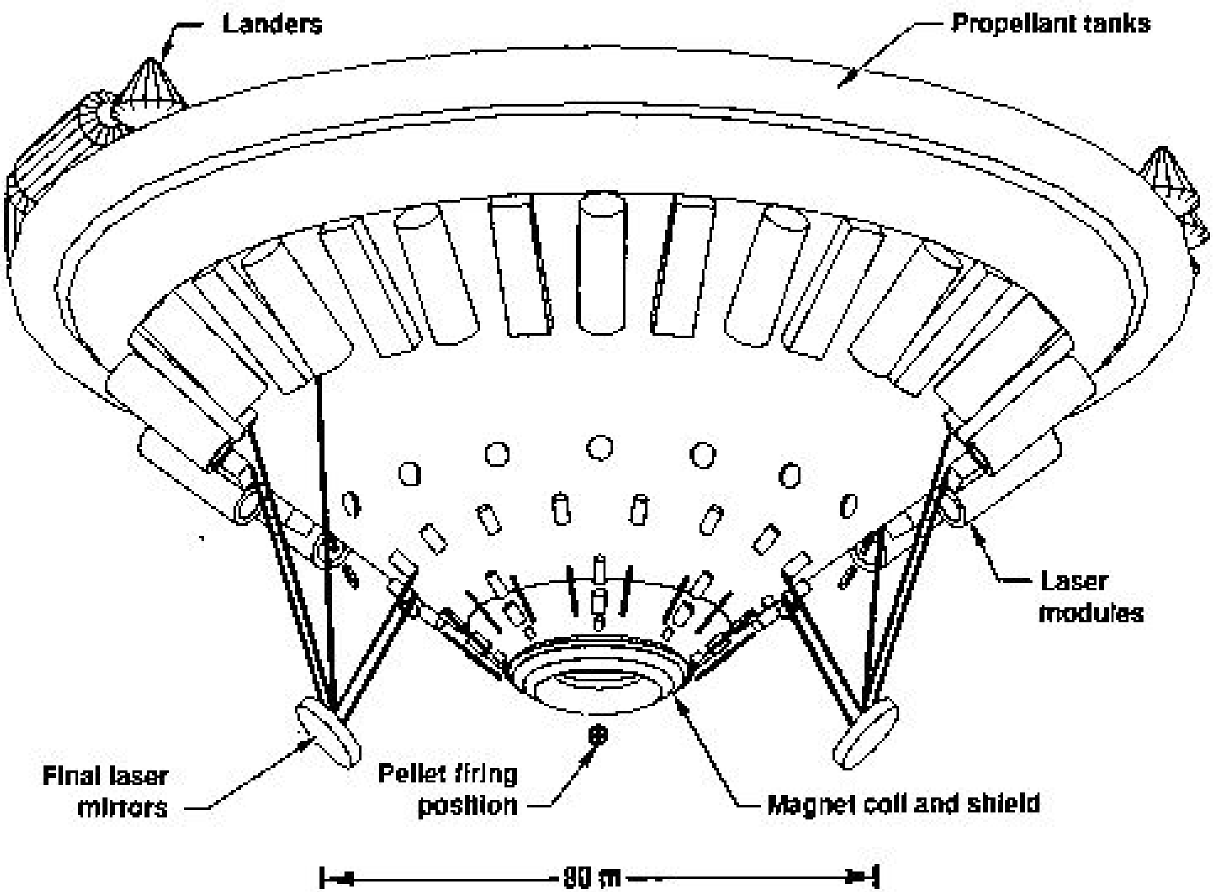
Barnes-Nebel, Penning Trap



Bussard, *Polywell*



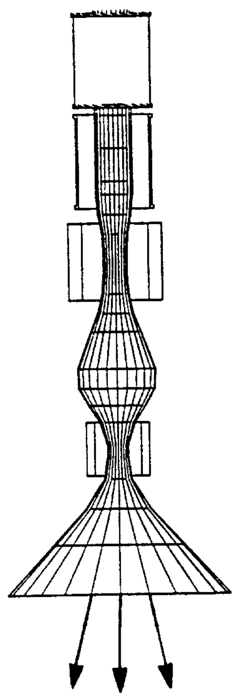
VISTA: Fusion Propulsion Using Inertial-Confinement Fusion (ICF)



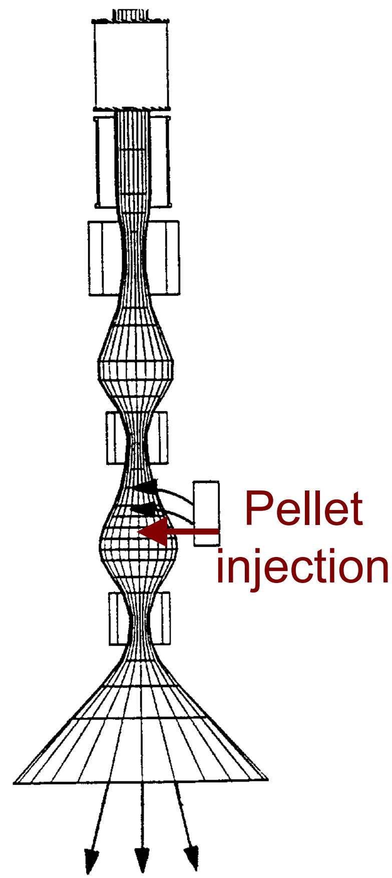
Charles Orth, et al., "The VISTA Spacecraft--Advantages of ICF for Interplanetary Fusion Propulsion Applications," IEEE 12th SOFE (1987).

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

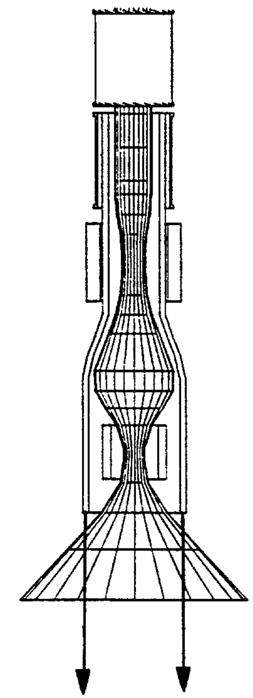
Fuel plasma exhaust



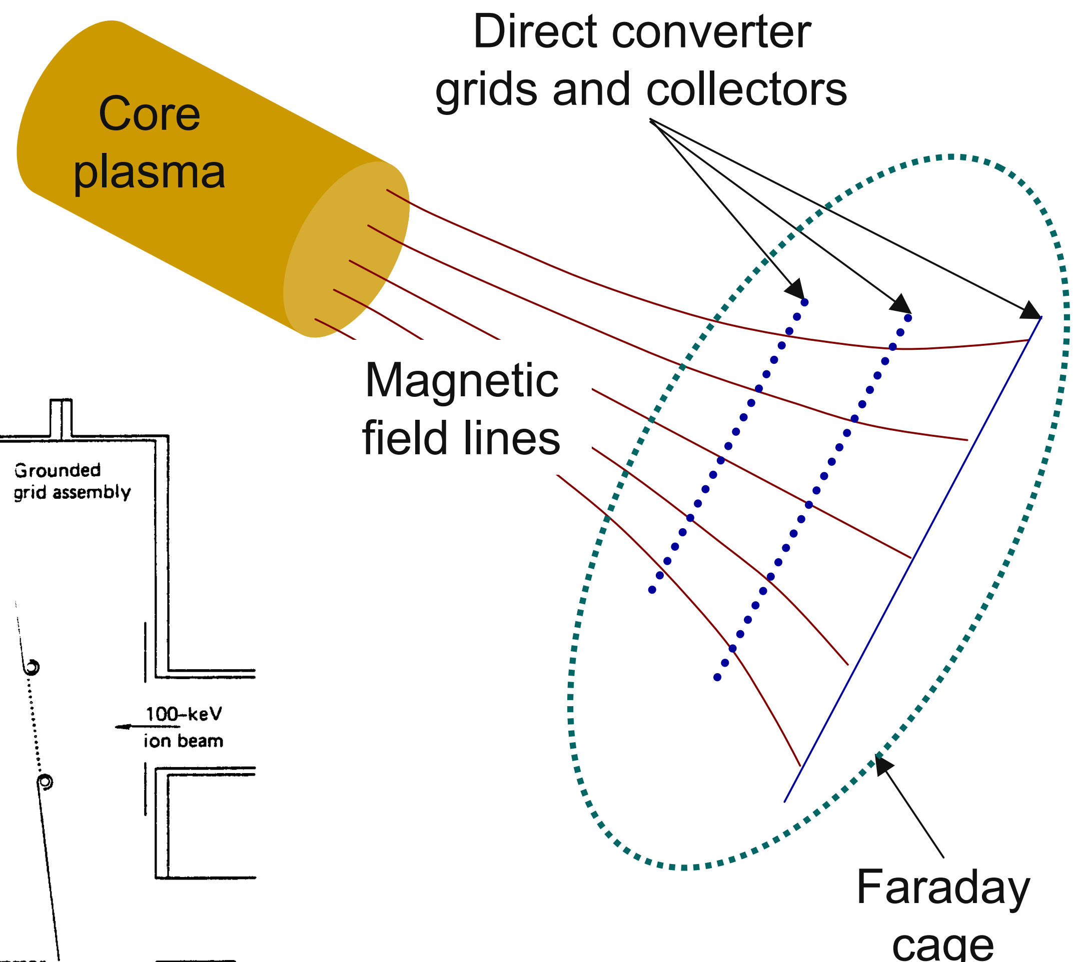
Mass-augmented exhaust



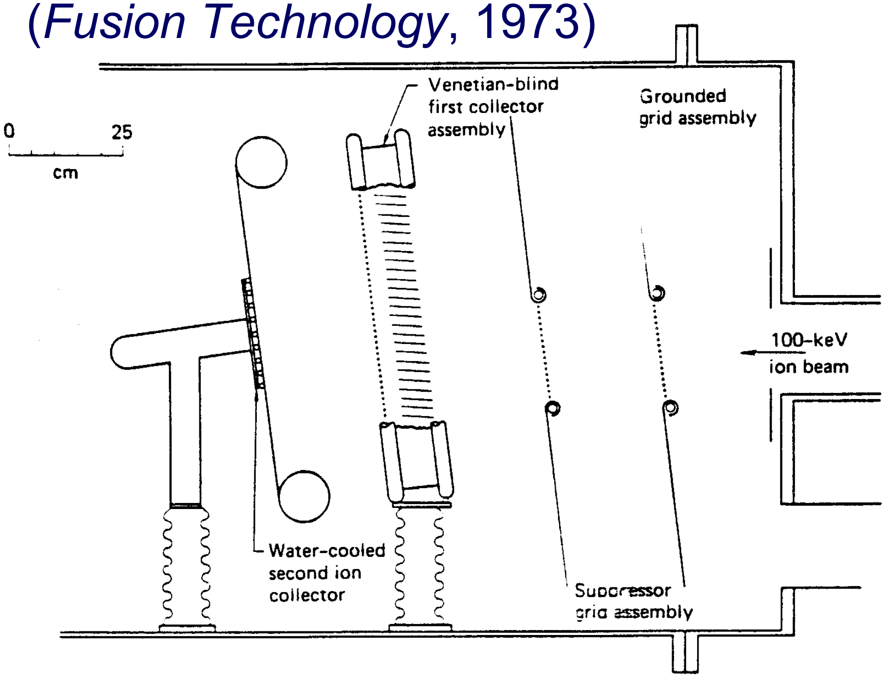
Thermal exhaust



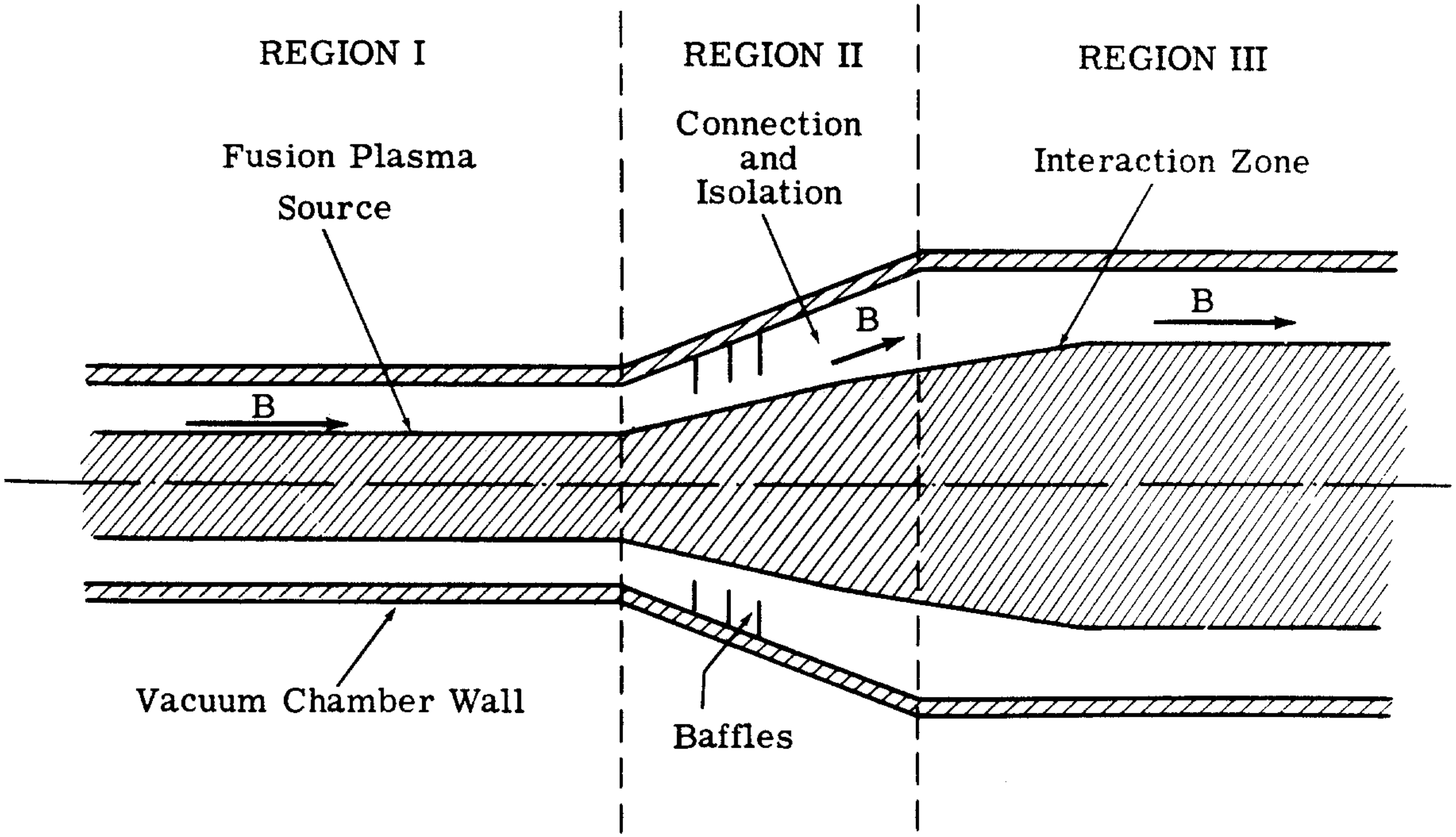
Direct Conversion to Electricity Could Take Advantage of the Natural Vacuum in Space



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.
- Successful development of D-^{3}He fusion would provide attractive propulsion, power, and materials processing capabilities.
- Several configurations appear promising for space propulsion, particularly the field-reversed configuration (FRC), spheromak, and spherical torus.