Fusion Space Propulsion Using Field-Reversed Configurations

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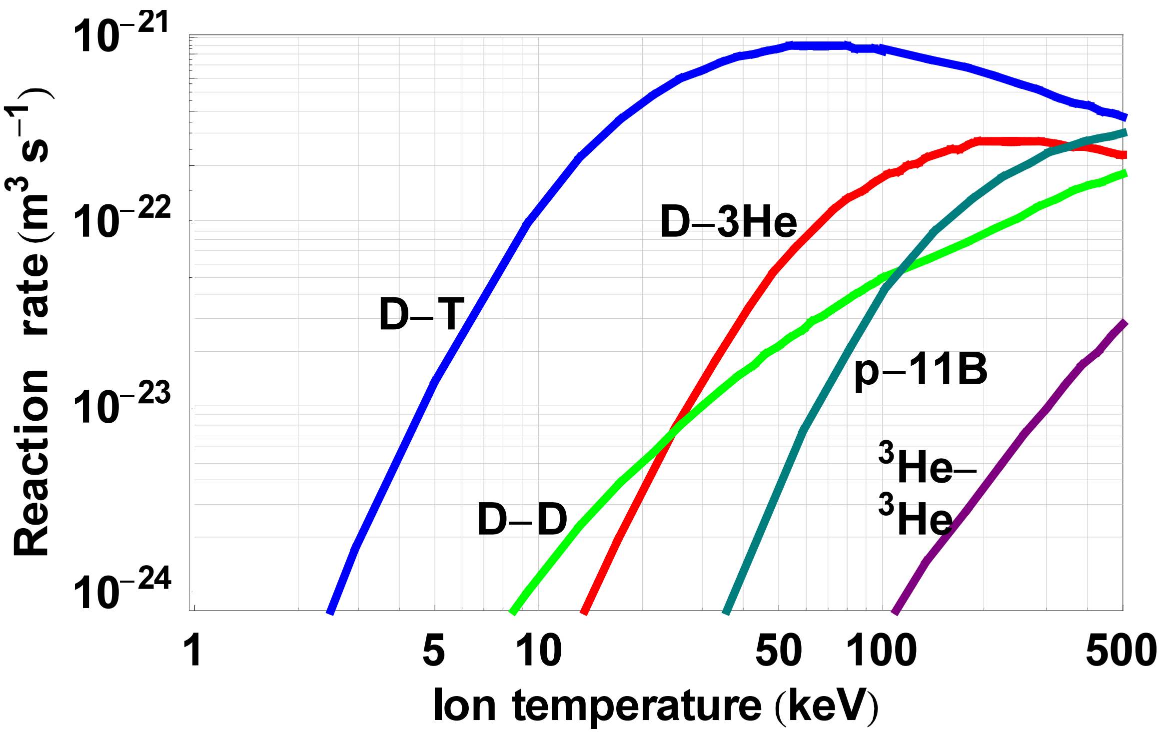
Key Fusion Fuel Cycles for Space Applications

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

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

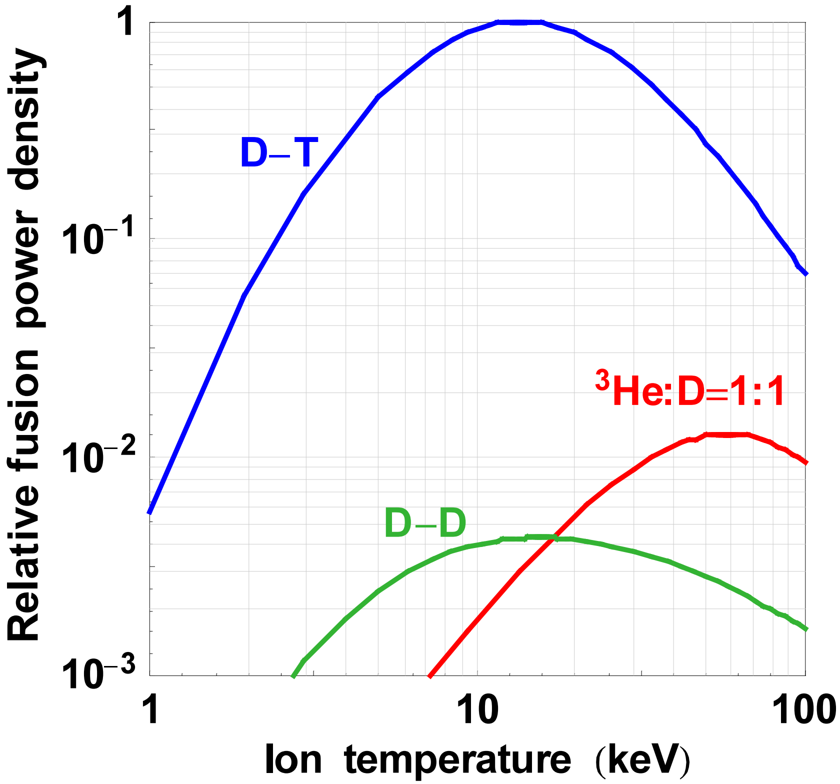
$D + D \rightarrow n\ (2.45\ MeV) + {}^3He\ (0.82\ MeV)$ {50%}

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

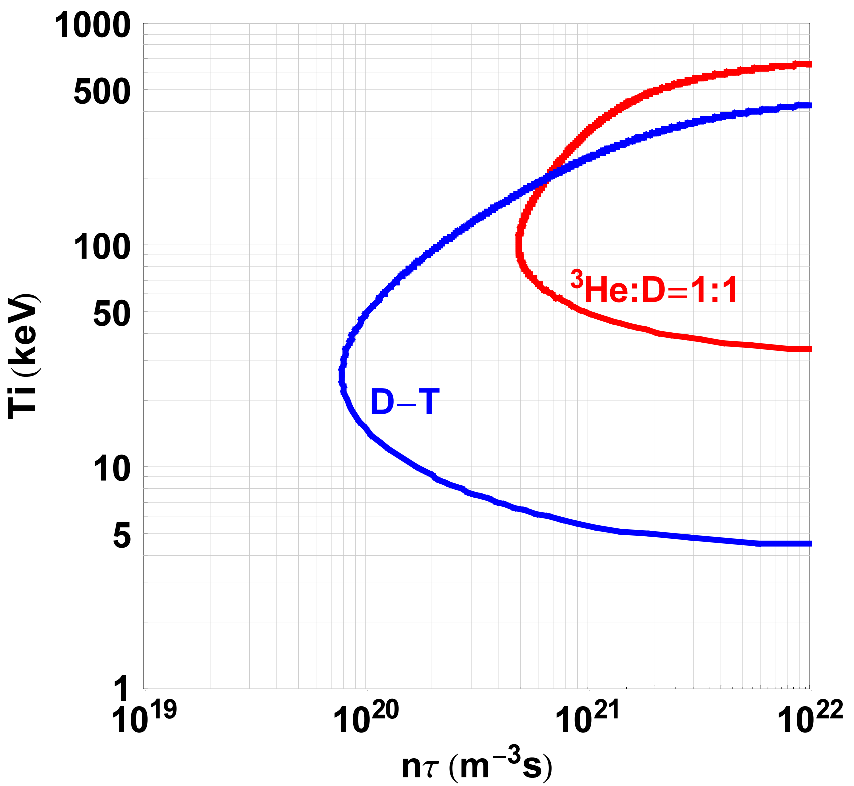


Physics Viewpoint: D-^{3}He Fuel Requires High β, nτ, and T

- Power density in the plasma must be increased by utilizing $\beta^2 B^4$ scaling.

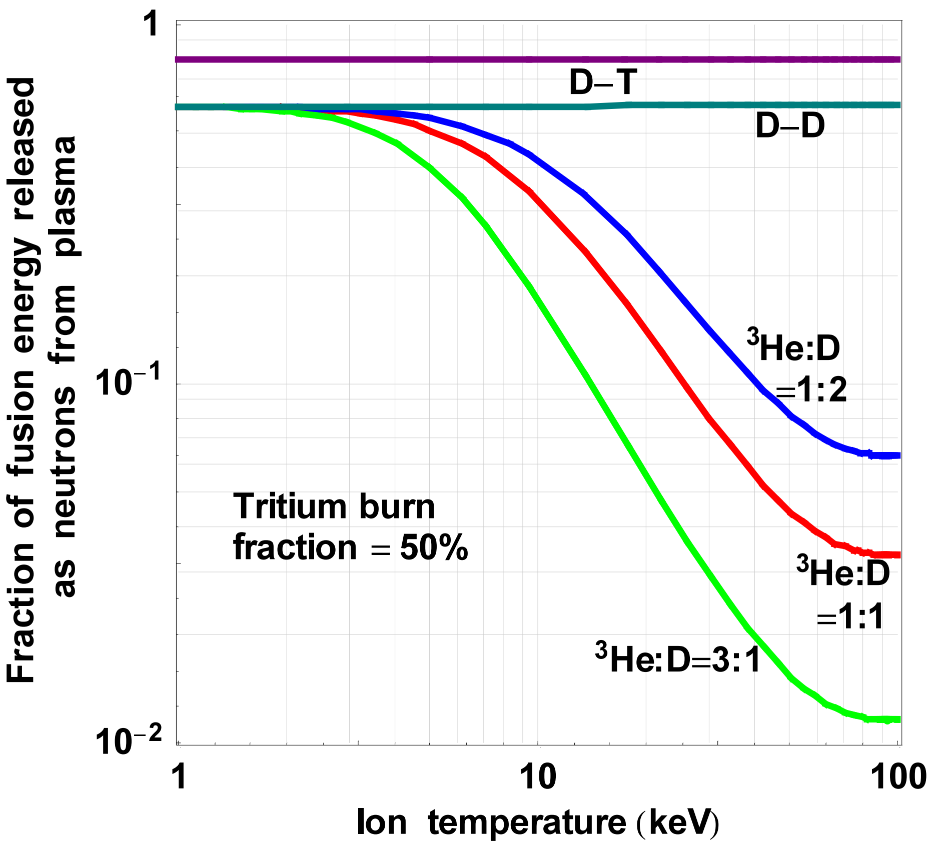


- T and $n\tau_E$ must each be ~4 to 5 times higher for D-^{3}He compared to D-T.



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



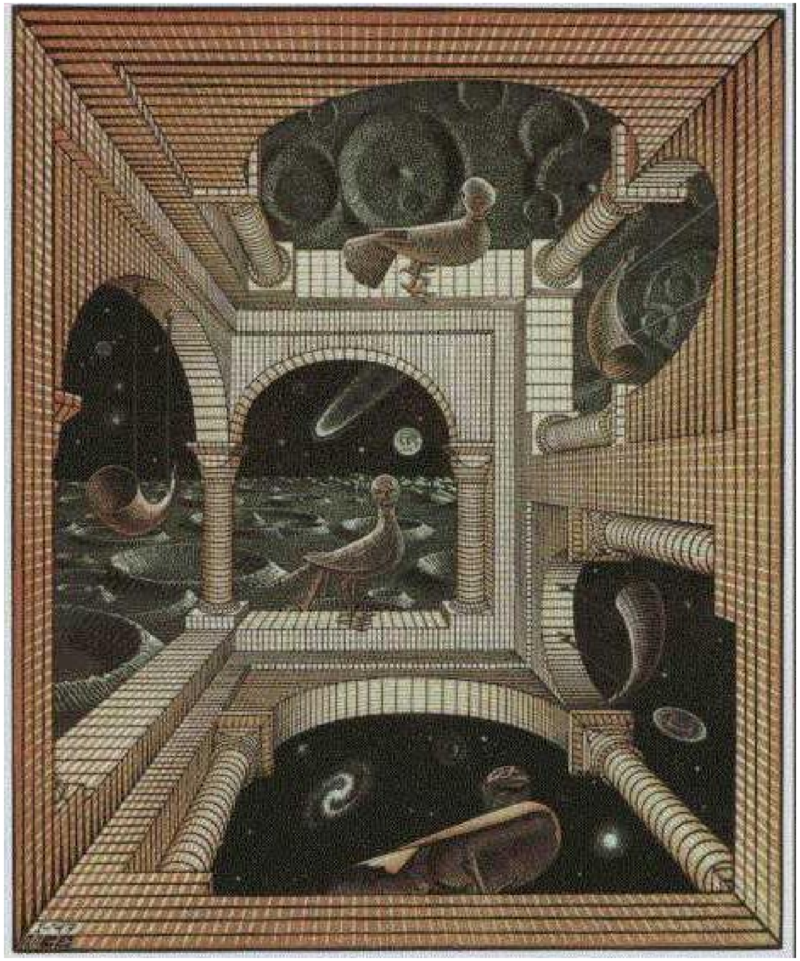
Sufficient Terrestrial ^{3}He Exists for an Engineering R&D Program

Reasonably Assured Reserves of He3 That Could Be Available in the Year 2000

Source	Cumulative Amount (kg)	Production Rate Post 2000 (kg/y)
TRITIUM DECAY		
•U.S. Weapons	300	15
•CANDU Reactors	10	2
PRIMORDIAL		
•He Storage	29	--
•Natural Gas	187	--
	>500	~17

- **500 kg ^{3}He ≈10 GW-y fusion energy**

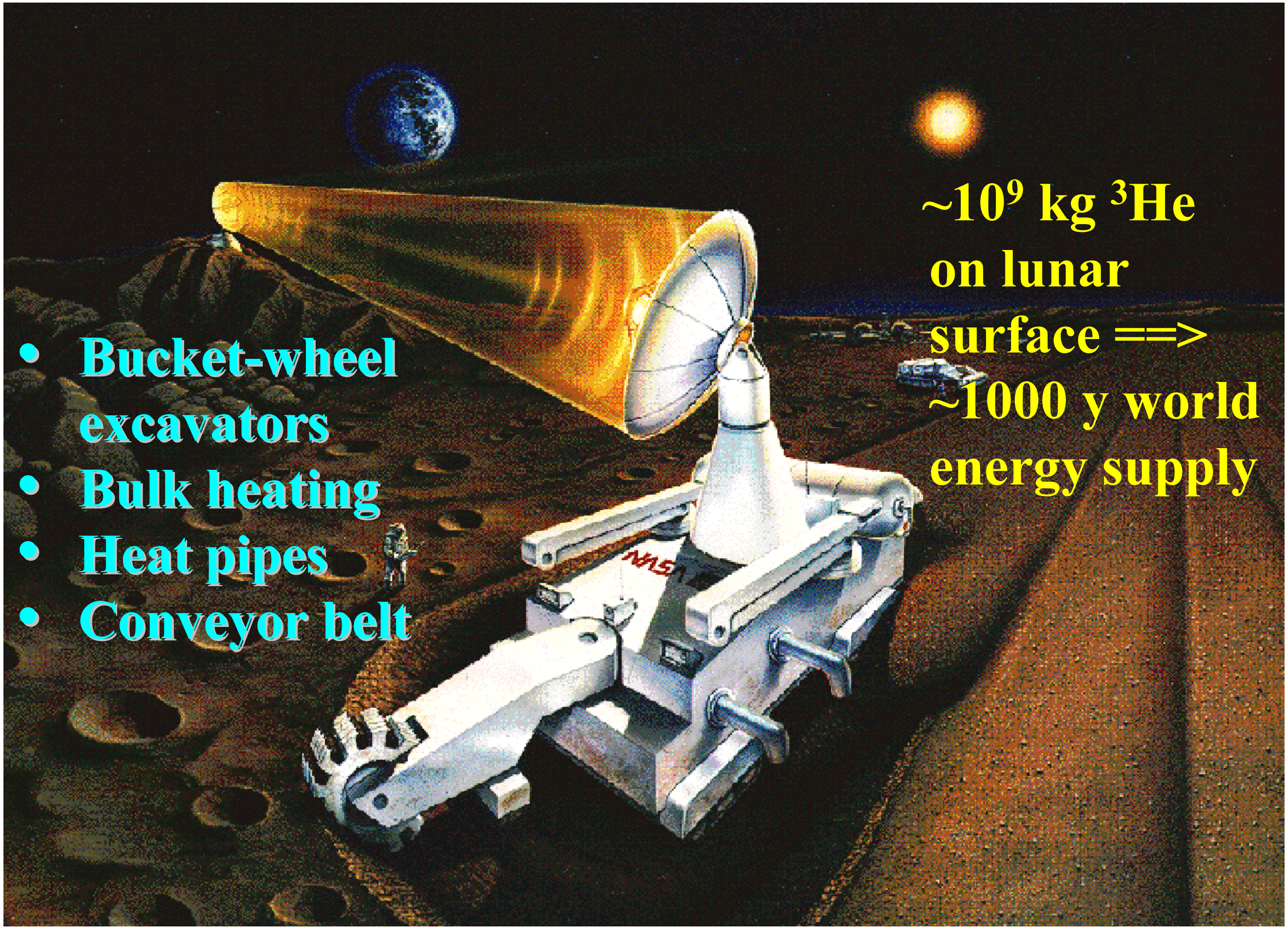
For ^{3}He Fuel, Think Outside the Box



Escher, Other World, 1947

- ~500 kg ^{3}He accessible on Earth (~10 GW-a fusion energy for R&D)
- ~10^9 kg ^{3}He on lunar surface for 21st century
- ~10^{23} kg ^{3}He in gas-giant planets for indefinite future

Well-Developed Terrestrial Technology Gives Access to ~10^9 kg Lunar ^3He

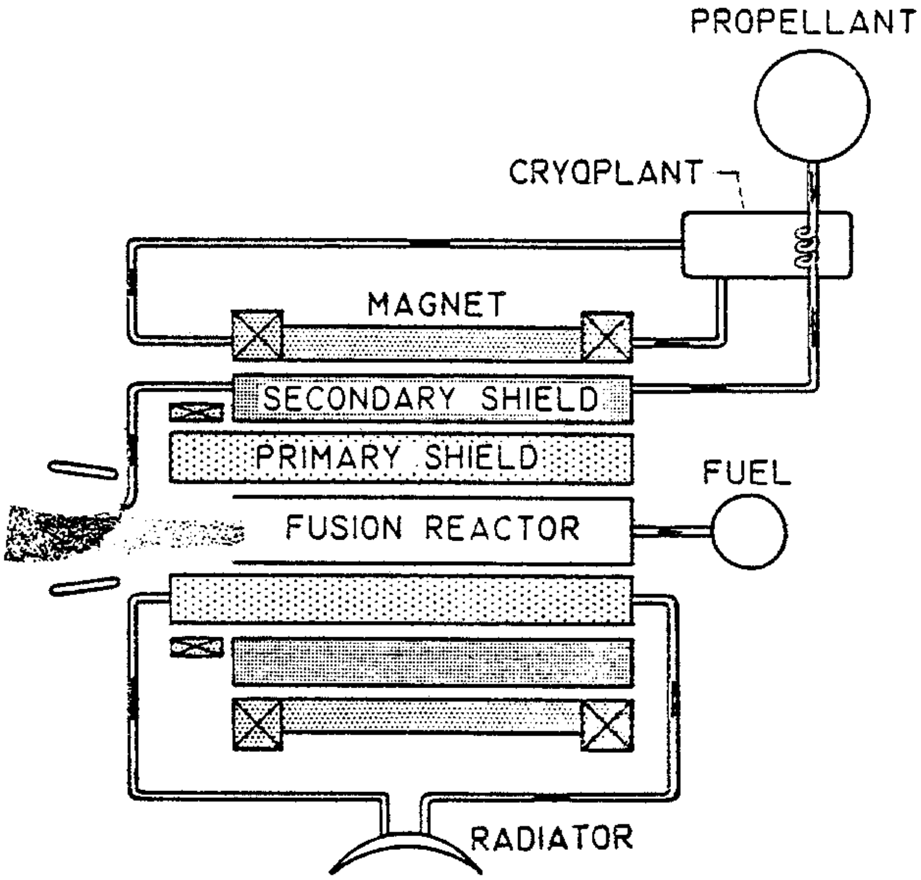


Earliest D-^{3}He Reactor Design Was a Fusion Rocket

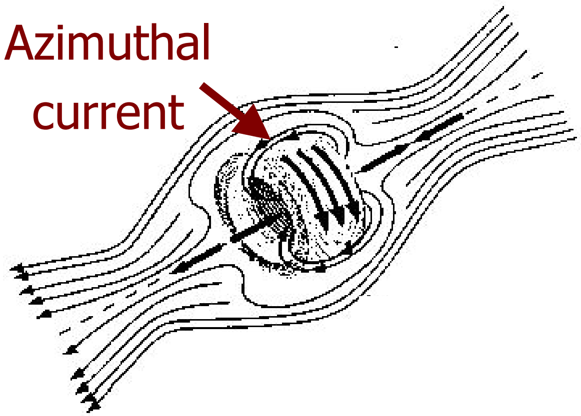
G.W. Englert,
NASA Glenn Research Center
New Scientist (1962)

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

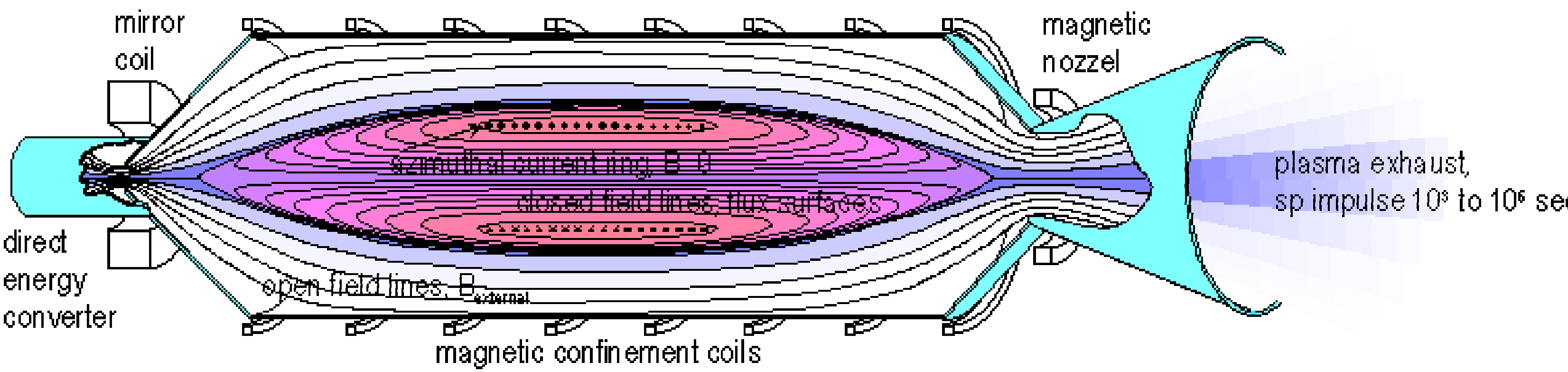
The application of superconducting magnets and a mixture of deuterium and helium-3 as fuel appears to be the most promising arrangement."



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



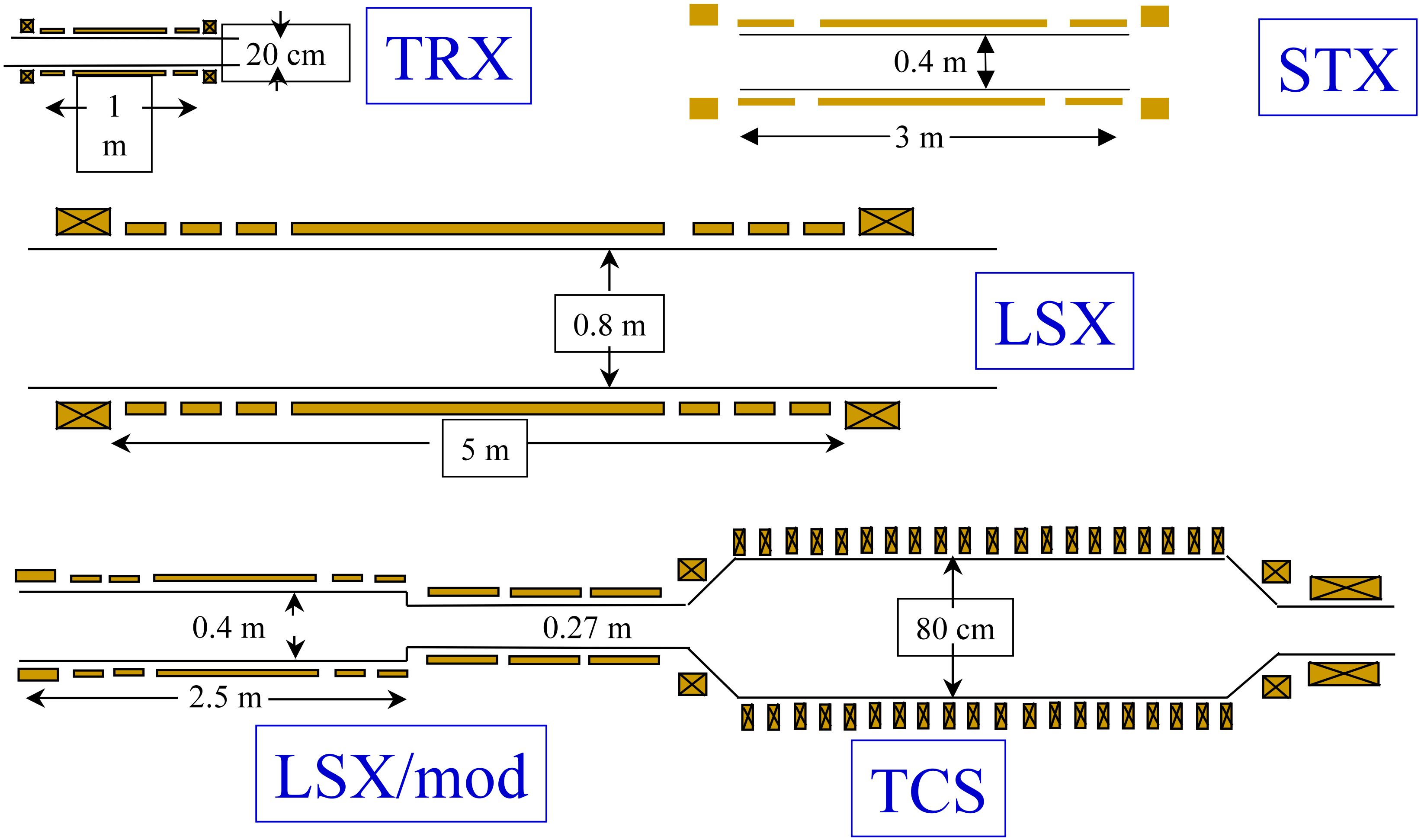
- High $\beta \equiv P_{plasma}/P_{B\text{-field}}$
- Linear external B field
- Cylindrical geometry
- RMF current drive



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

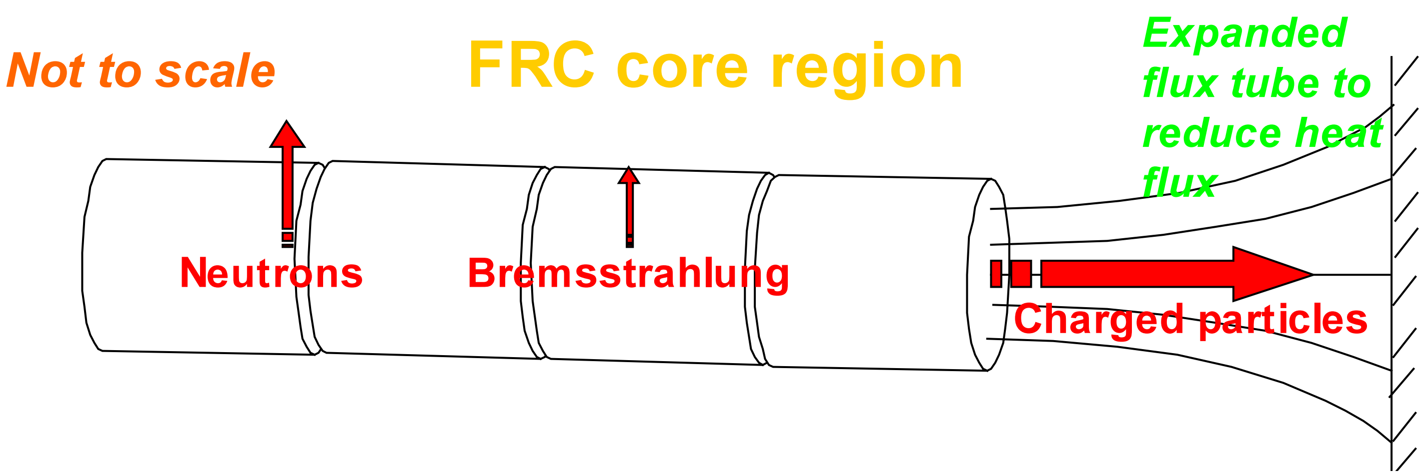
Past & Present
Univ. of Washington Experimental Facilities



from Alan Hoffman

FRC Plasma Power Flows Differ Significantly from Tokamak Power Flows

- 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.

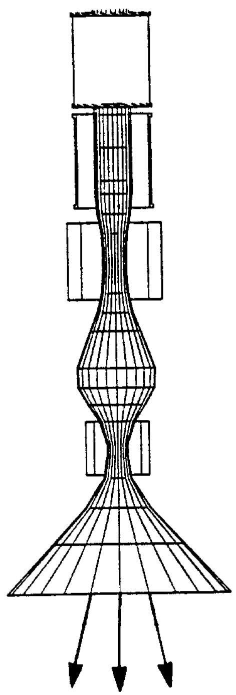


Linear Geometry
Greatly Facilitates Engineering

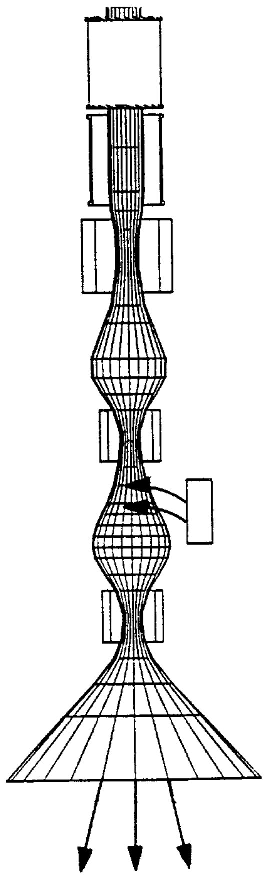
- Steady-state heat flux is broadly spread and due almost exclusively to bremsstrahlung radiation power.
- Relatively small peaking factor along axis for bremsstrahlung and neutrons.
- Maintenance of single-unit modules containing blanket, shield, and magnet should be relatively easy, improving reliability 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.

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

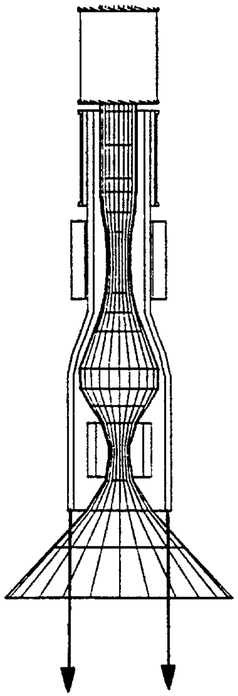
Fuel plasma exhaust



Mass-augmented exhaust



Thermal exhaust



Predicted Specific Power of D-^{3}He Field-Reversed Configuration Rockets is 5-10 kW/kg

- Prediction based on J.F. Santarius and B.G. Logan, "Generic Magnetic Fusion Rocket," *Journal of Propulsion and Power* **14**, 519 (1998).
- Detailed analysis tends to reduce predictions, but the development of high-temperature superconductors will reduce the power-plant mass.
  - Reduced refrigerator mass for magnet coolant.
  - Reduced shielding, because more magnet heating can be tolerated before quenching.
- Work is in progress to apply a more sophisticated analysis to D-^{3}He FRC rockets.

Summary

- The projected performance of D-^{3}He field-reversed configuration (FRC) fusion rockets would allow fast, efficient Solar-System travel.
- The FRC approach constitutes a leading magnetic fusion concept for space applications because of its high power density capability and linear geometry.
- FRC physics development remains the key issue, because the reduced neutron production from D-^{3}He compared to D-T fusion eases engineering development.