Role of Advanced-Fuel and Innovative Concept Fusion in the Nuclear Renaissance

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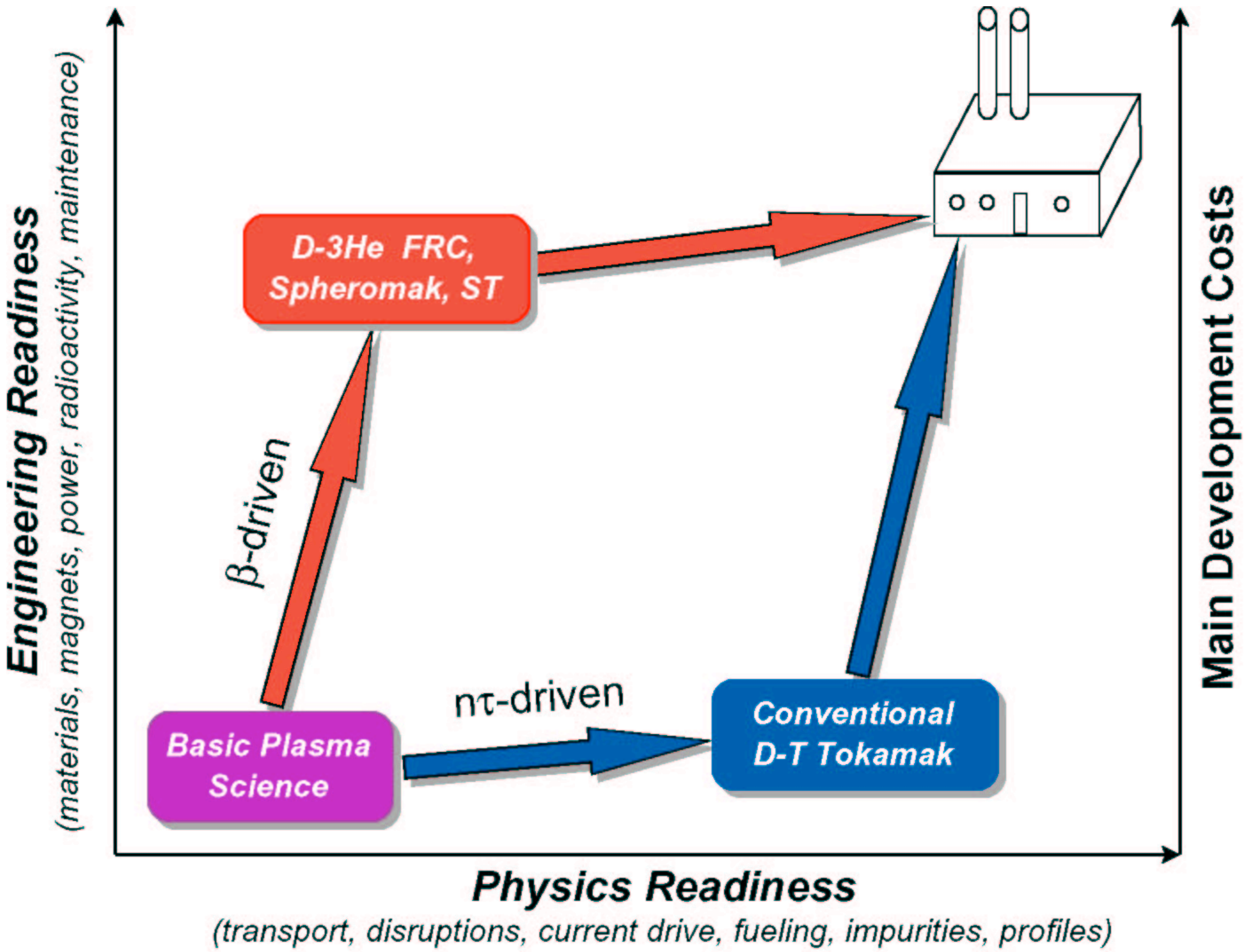
Why Investigate Advanced Fuels and Innovative Fusion Concepts?

- Fusion development requires physics, engineering, safety, and environmental progress.
- D-T tokamaks dominate present fusion development because of their physics advantages.
- Assuming modest plasma physics progress, what other fusion options emerge?
- This talk will examine advanced fuels and innovative fusion concepts with respect to all four development areas.

Main Thesis of This Talk: D-^{3}He Fuel Could Lower R&D Costs

- Engineering R&D costs typically dominate physics R&D costs.



Advanced Fusion Fuels
Greatly Reduce Neutron Production

1st generation fuels:

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

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

$\rightarrow p\ (3.02\ MeV) + T\ (1.01\ MeV)$

{50% each channel}

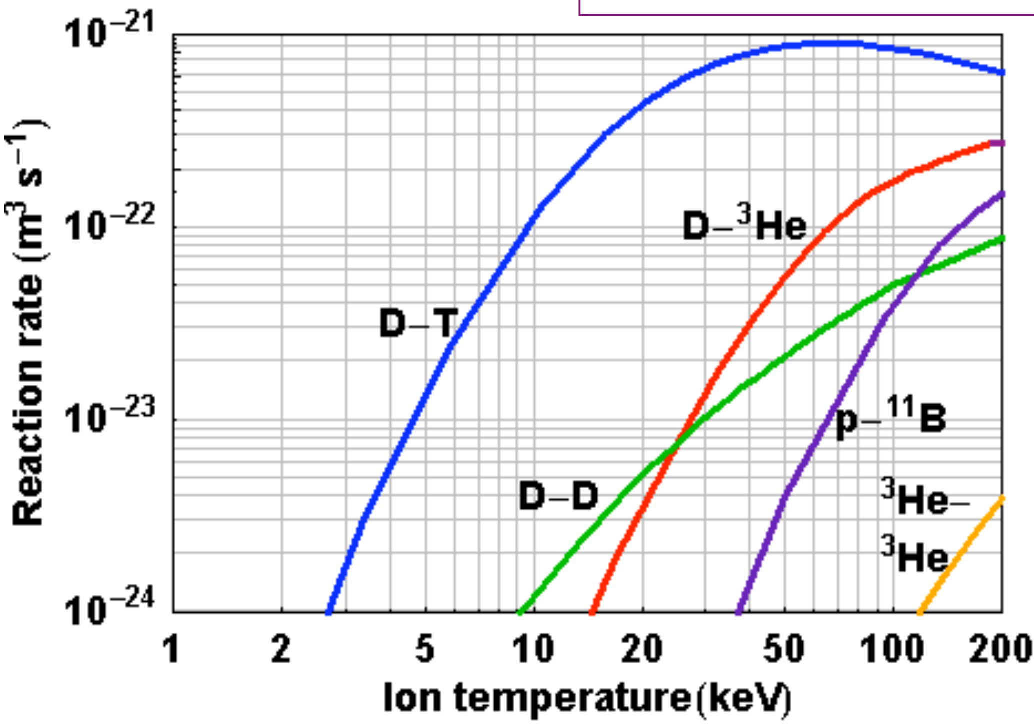
2nd generation fuel:

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

3rd generation fuels:

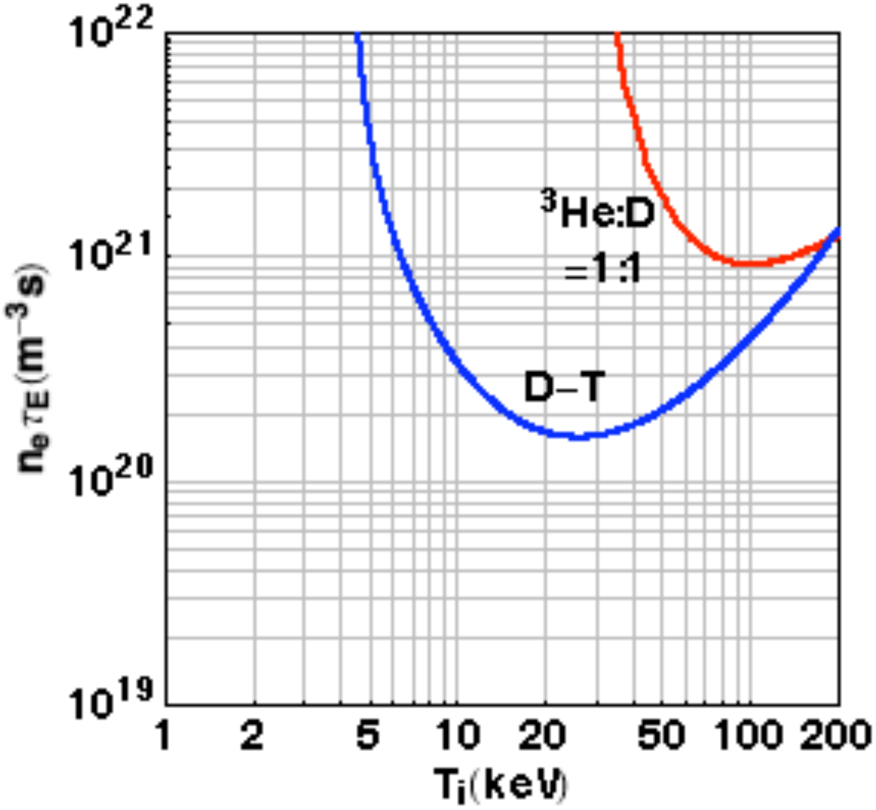
${}^3He + {}^3He \rightarrow 2\ p + {}^4He\ (12.86\ MeV)$

$p + {}^{11}B \rightarrow 3\ {}^4He\ (8.68\ MeV)$



D-^{3}He Fuel Faces Larger Physics Obstacles than D-T

Ignition contours against bremsstrahlung

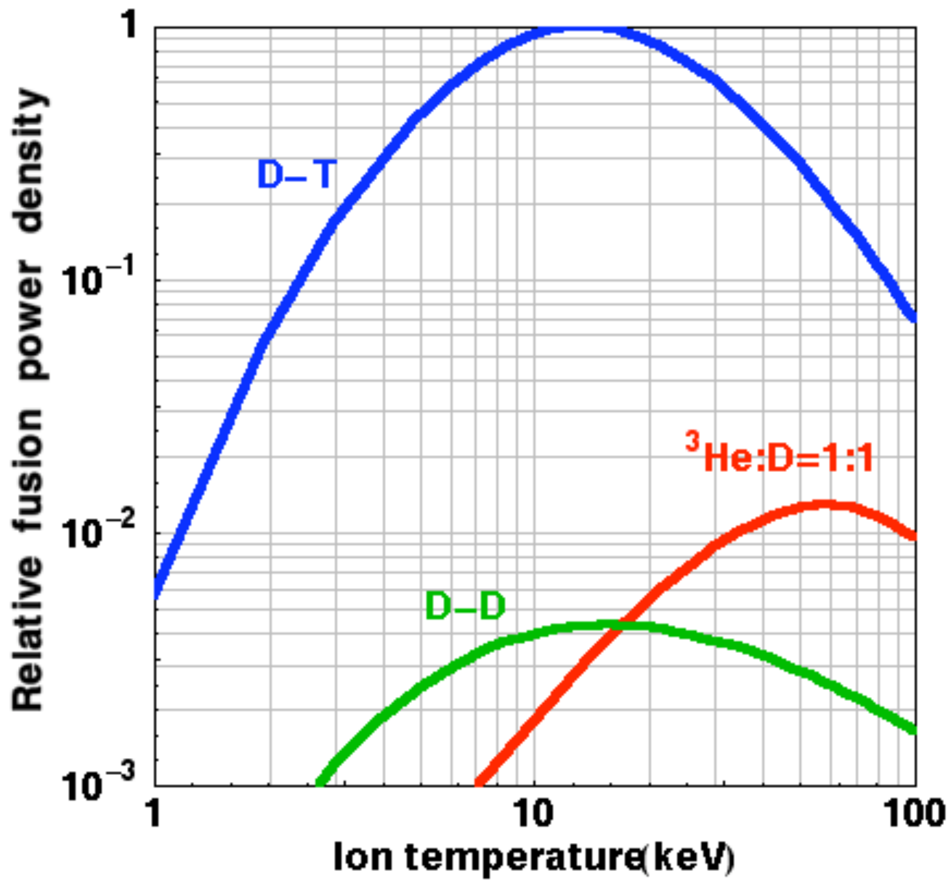


- D-^{3}He, compared to D-T, requires:
  - Minimum factor of ~6 increase in ignition temperature,
  - Minimum factor of ~8 $n_e\tau_E$ increase,
  - Minimum Tnτ increase of ~50 times (^{3}He:D density = 1:2).
- D-^{3}He fusion relies on continued plasma physics progress that improves modestly over the impressive physics development already achieved.

D-^{3}He Needs a Factor of ~80 Above D-T Fusion Power Densities

- However, note that:
  - Neutron wall loads limit D-T fueled innovative concepts well before they reach β (plasma pressure / magnetic-field pressure) or B-field limits.
  - Fusion power density scales as $\beta^2 B^4$.
  - Only for concepts with very low limits on β of 5-10% do optimized reactor design B-fields approach the technological limits on the magnet coils.

Relative Power Density at Constant β

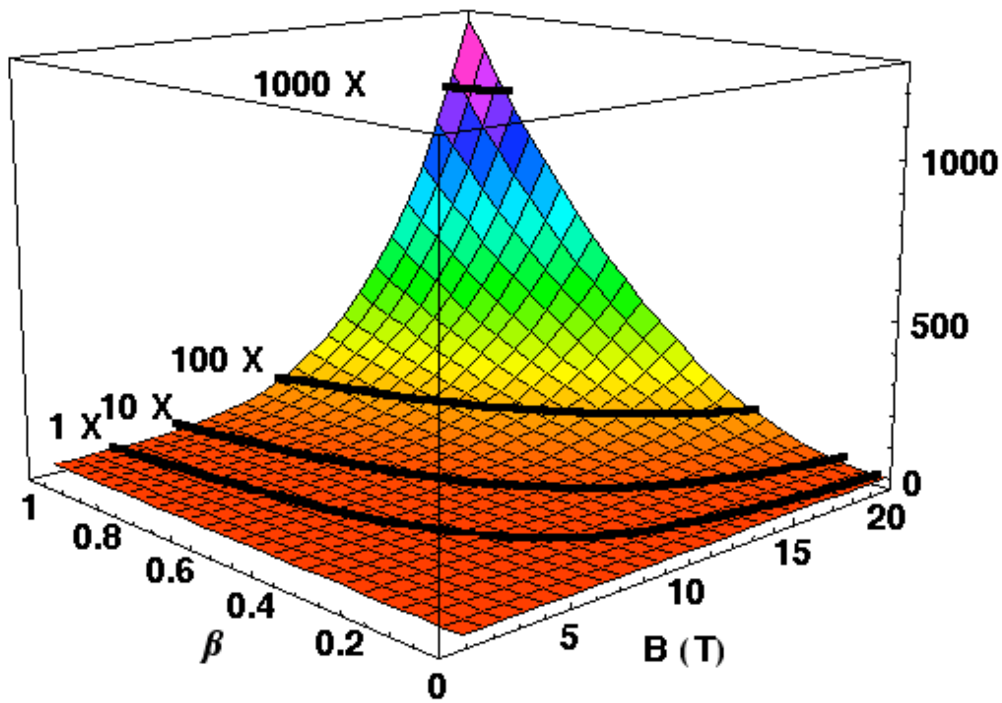


D-^{3}He Could Have a Power Density at Least as High as D-T Power Density

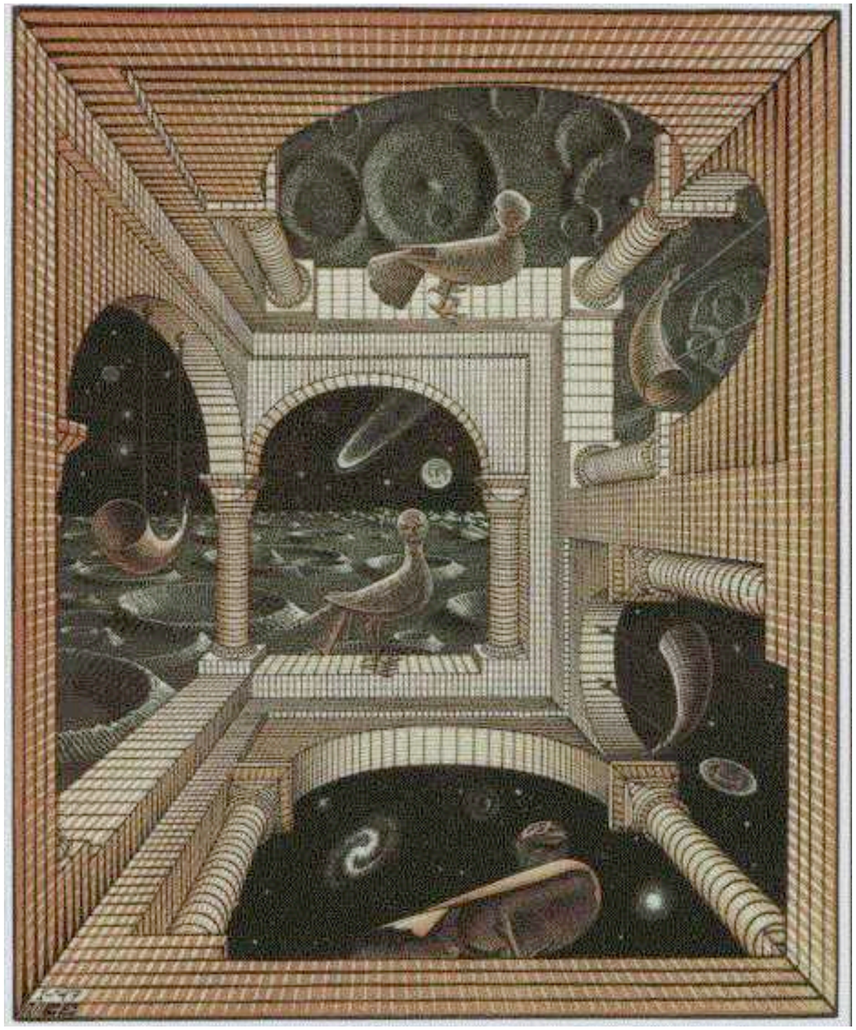
- D-T fueled FRC reactors (β ~85%) optimize at B ≤ 3 T.
- Superconducting magnets can attain at least 20 T, especially in solenoidal geometry.
- Fusion power density scales as $\beta^2 B^4$, allowing concepts with high values of these parameters to increase their power density to neutron wall load or surface heat load limits.

Power density improves greatly through increasing β and B-field

Power density relative to a D-T FRC with β=0.85 and B=3 T



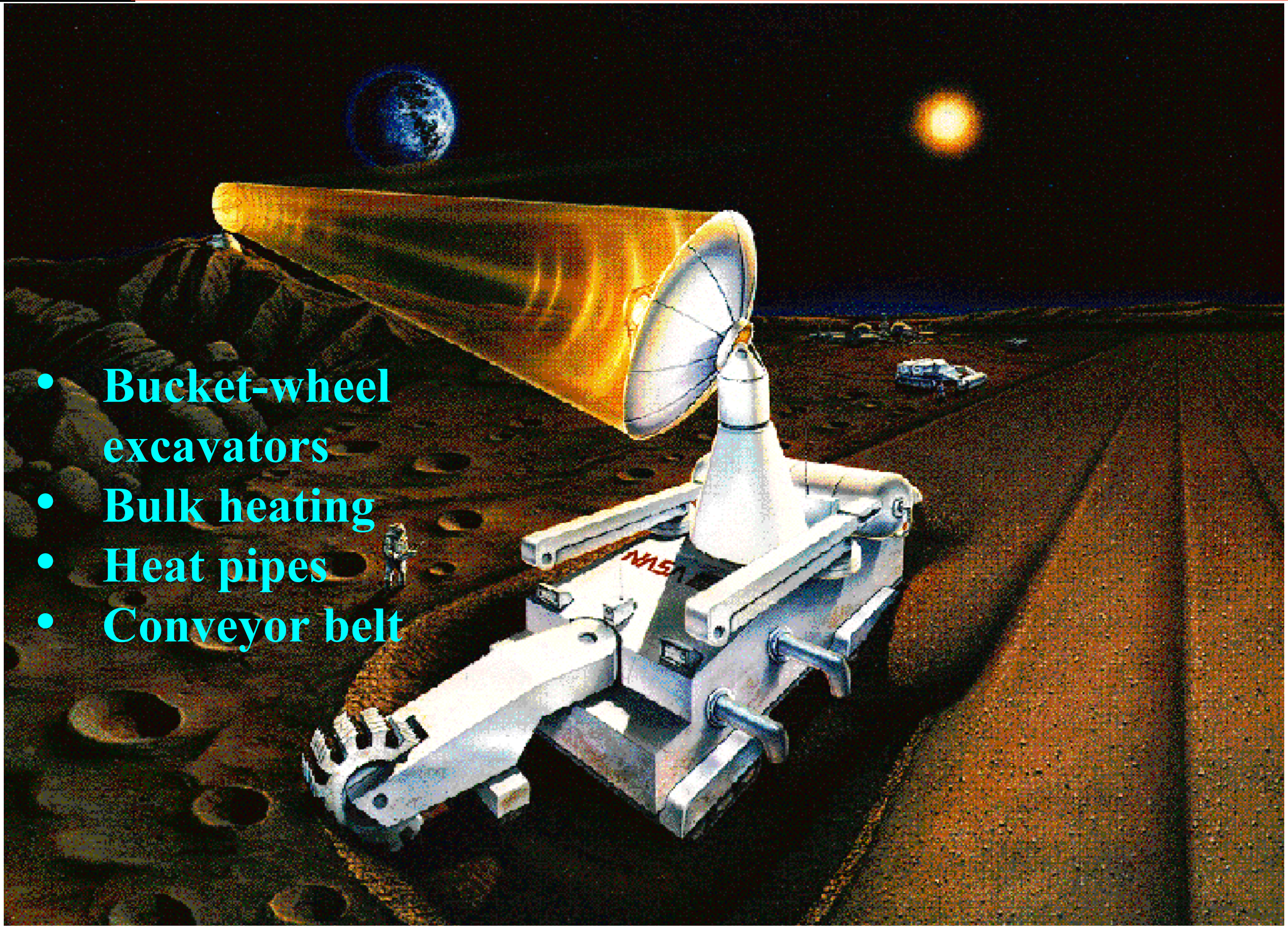
For ^{3}He Fuel, Think Outside the Box



Escher, Other World, 1947

- ~400 kg ^{3}He accessible on Earth
  - ~8 GW-y fusion energy for R&D
- ~10^9 kg ^{3}He on lunar surface for 21st century
  - ~1000 y world energy supply
- ~10^{23} kg ^{3}He in gas-giant planets for indefinite future
  - ~10^{17} y of world energy supply

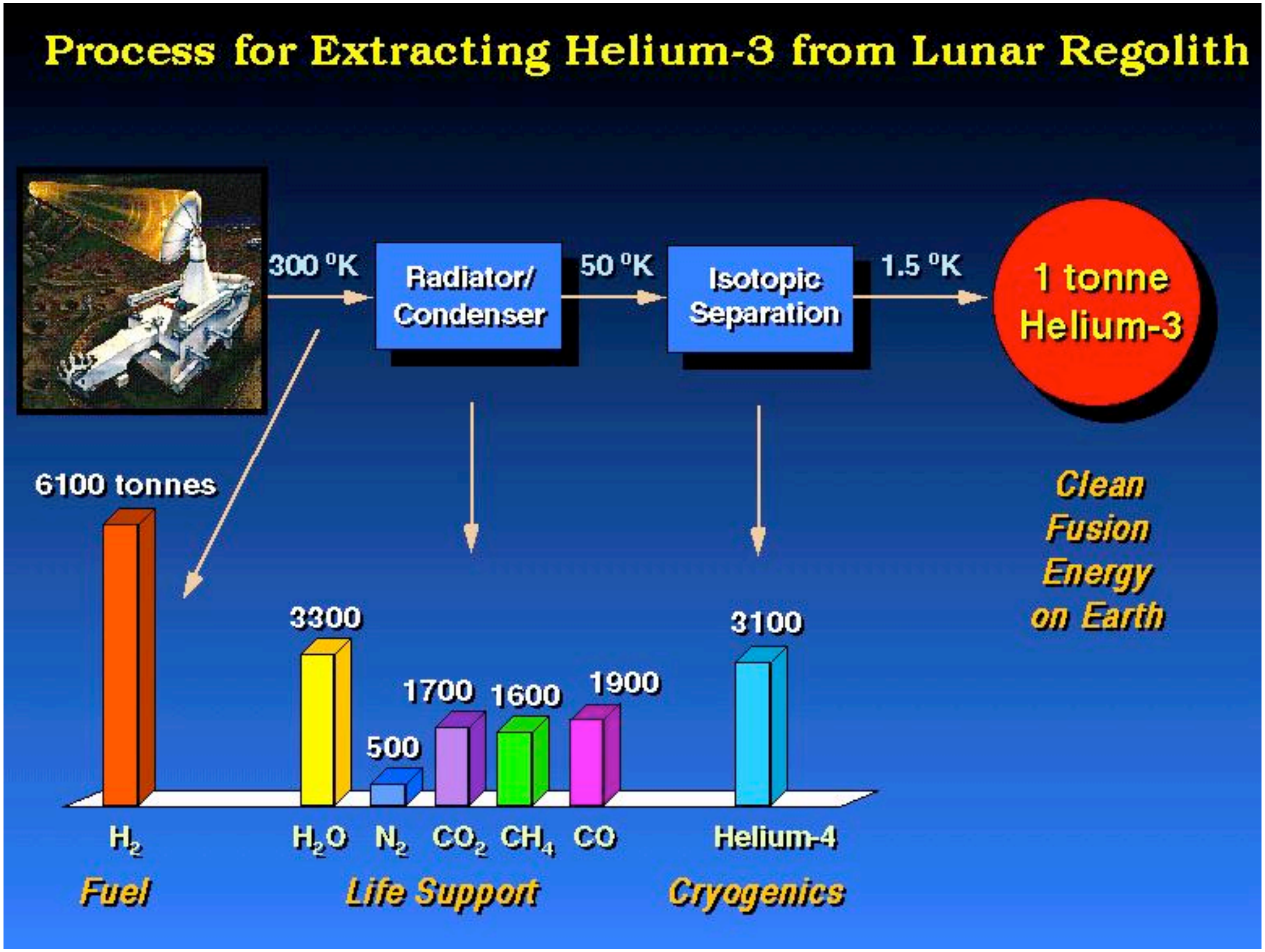
Well-Developed Terrestrial Technology Gives Access to ~10^9 kg of Lunar ^{3}He



- One miner:
  - Produces 33 kg ^{3}He plus many tonnes of *useful* volatiles yearly.
  - Mines 1 km^2 lunar area per year to 3 m depth.

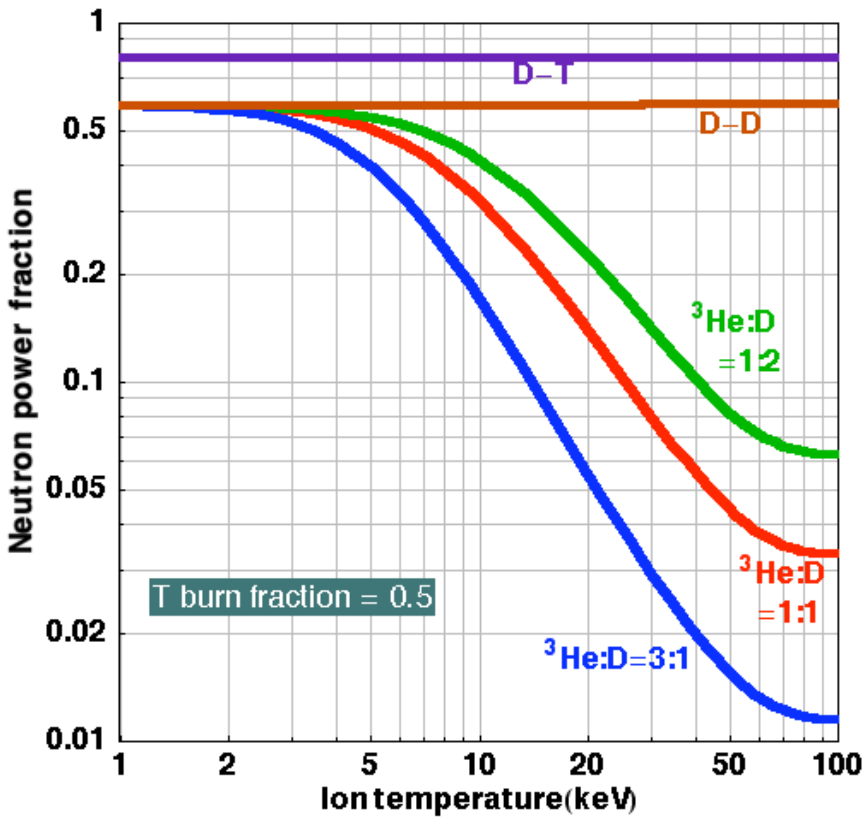
L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technology* **10**, 167 (1986)

Lunar ^3He Mining Produces Other Volatiles Useful for Life Support, Chemical Rocket Fuel, and Other Applications



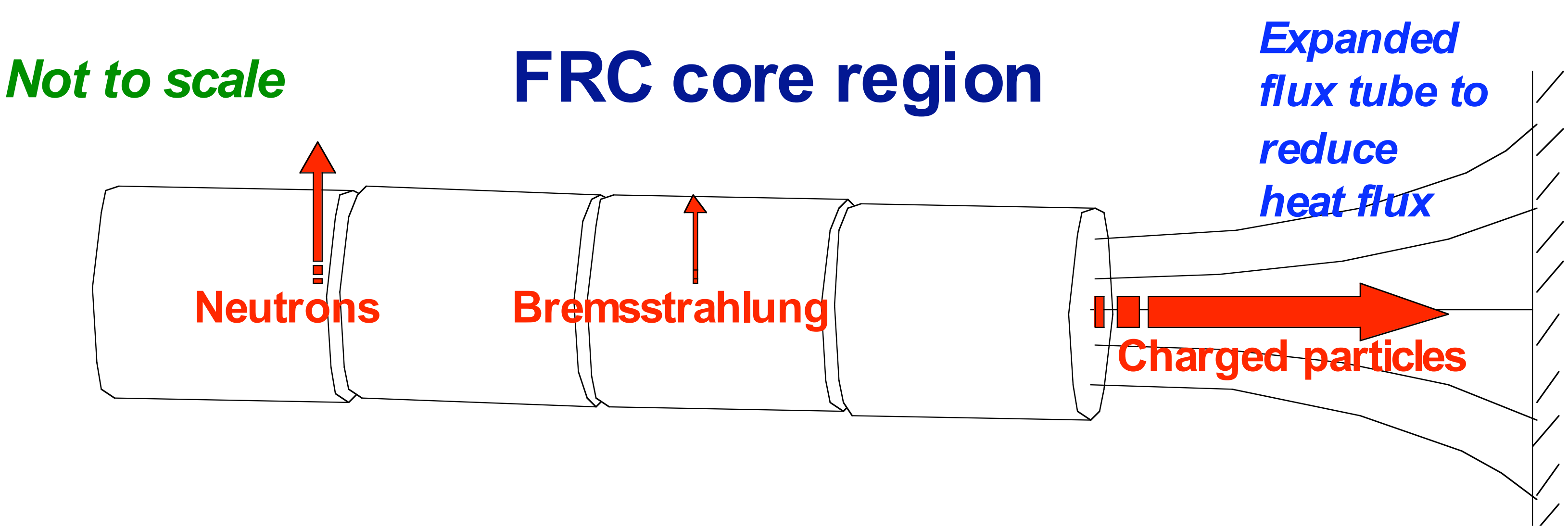
D-^{3}He Fuel Generally Gives Easier Engineering and Safety

- Reduced neutron flux allows
  - Smaller radiation shields
  - Smaller magnets
  - Permanent first wall and shield
  - Easier maintenance
- Increased charged-particle flux allows direct energy conversion
- Unburned tritium will be a proliferation and safety issue

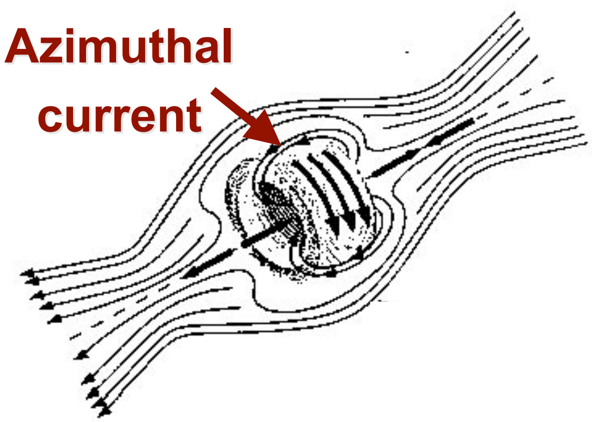


Linear Geometry Provides Solution to Handling Charged-Particle Surface Heat Flux

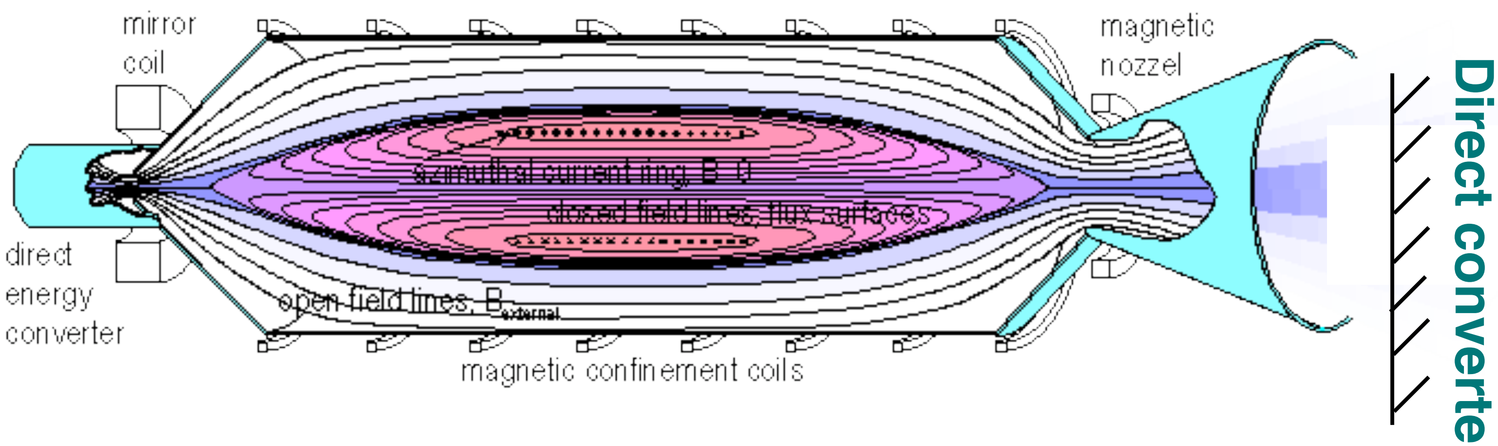
- Charged-particle power transports from internal plasmoid (in an FRC or spheromak) to edge region and then out ends of fusion core.
- Expanded flux tube in end chamber reduces heat and particle fluxes.
- Mainly bremsstrahlung power contributes to first-wall surface heat.
- Relatively small peaking factor along axis for bremsstrahlung and neutrons.



Field-Reversed Configuration (FRC) Matches D-^{3}He Fuel Well and Would Be Attractive for Fusion Power



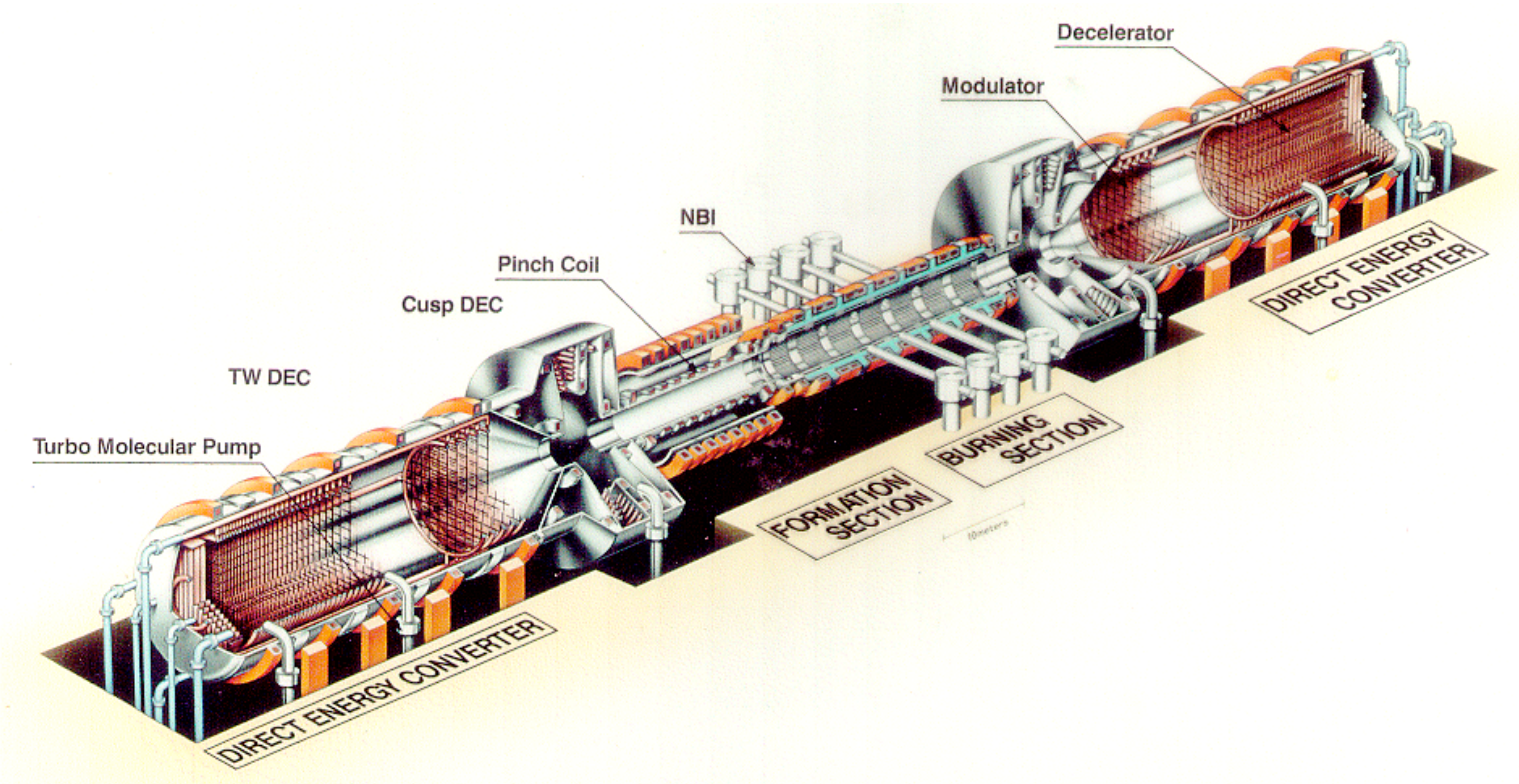
- Very high $\beta \equiv P_{plasma}/P_{B\text{-field}}$
- Linear external B field
- Cylindrical geometry
- Requires efficient current drive
  - Good rotating B-field progress



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

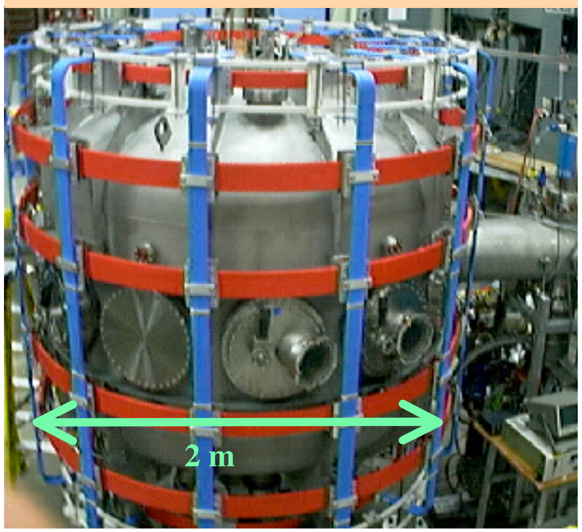
ARTEMIS Field-Reversed Configuration
(D-^{3}He, Momota, et al., NIFS, 1992)



Some Candidate Advanced Fusion Concepts
(Not Exclusive)

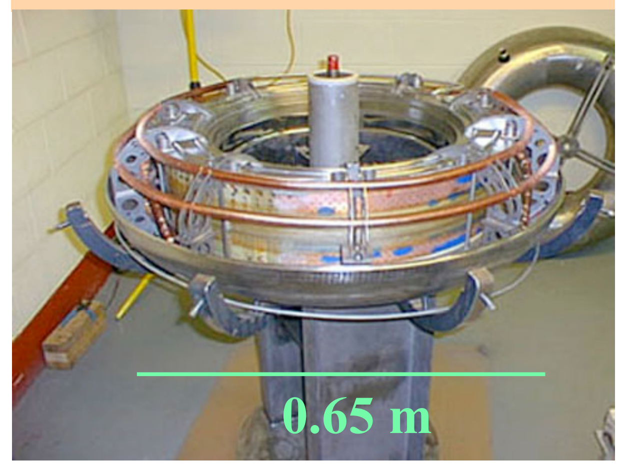
Field-Reversed Configuration (FRC)

Spherical Torus (ST)



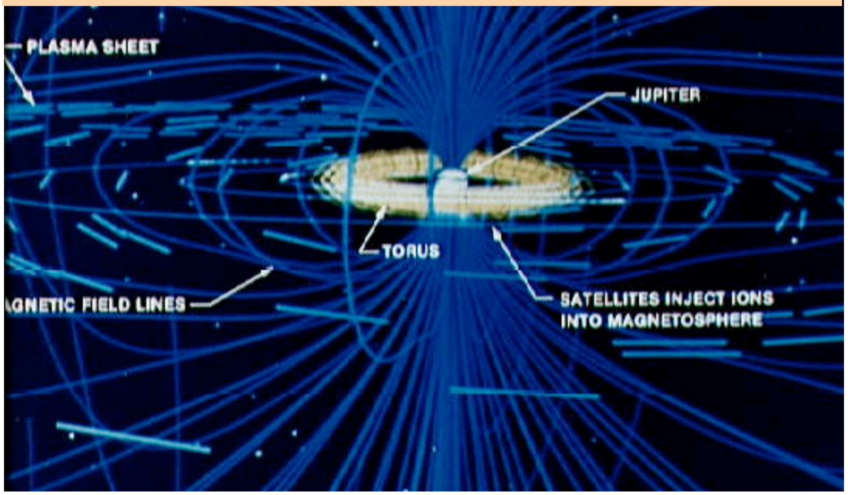
Spheromak

Dipole

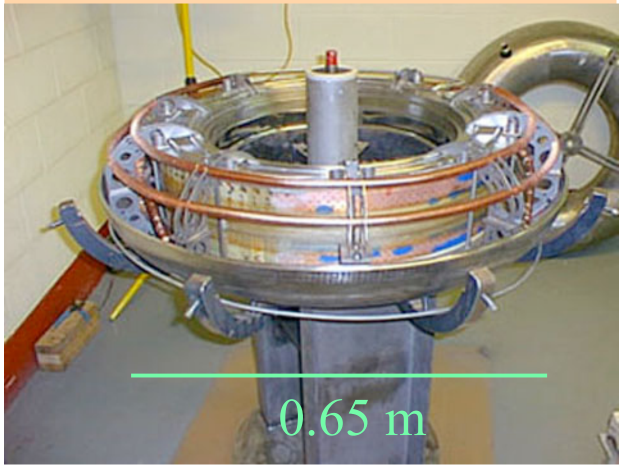


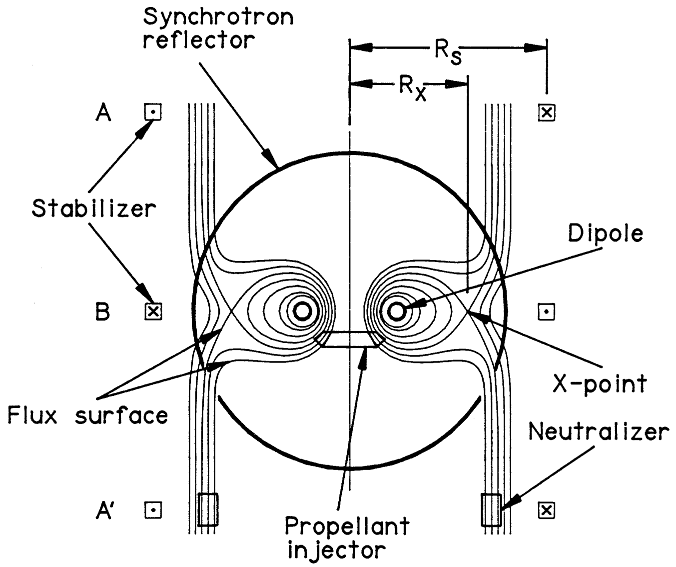
The Dipole Configuration Offers a Relatively Simple Design That an MIT/Columbia Team Has Begun Testing

Io plasma torus around Jupiter



LDX experiment (MIT)





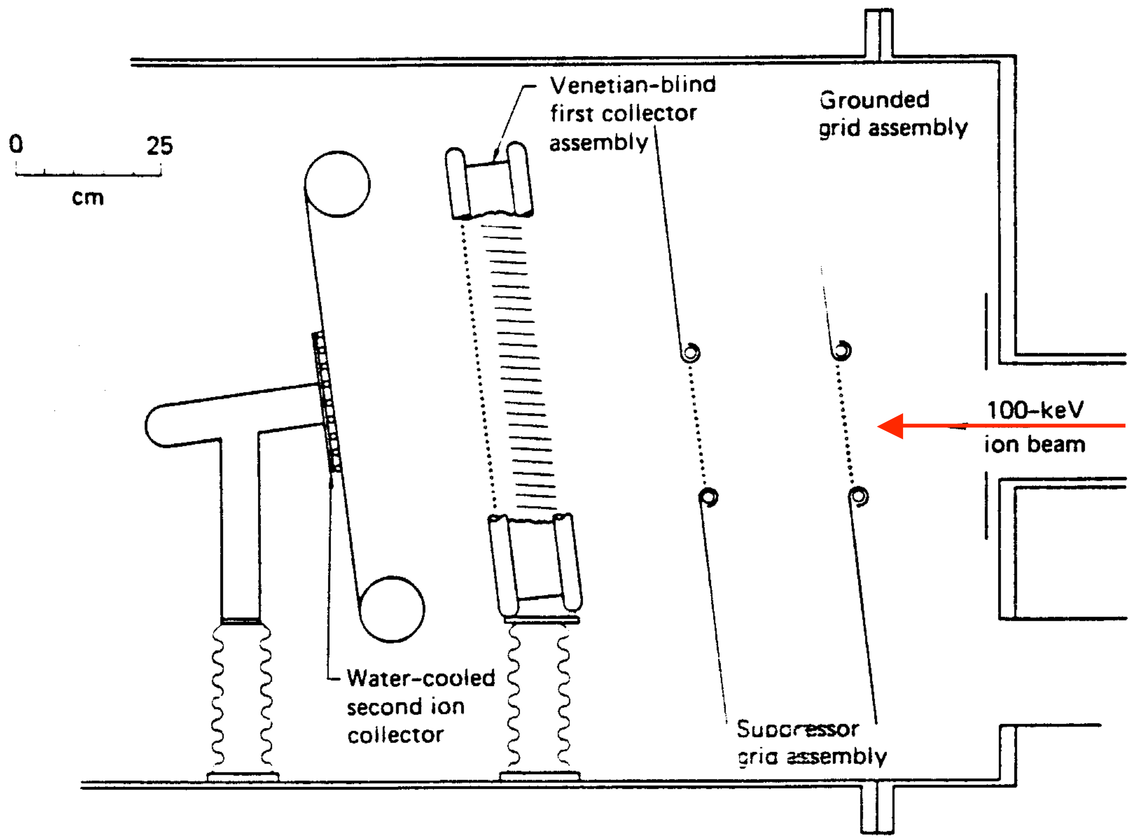
Dipole space propulsion design:

E. Teller, et al., *Fusion Technology* **22**, 82 (1992).

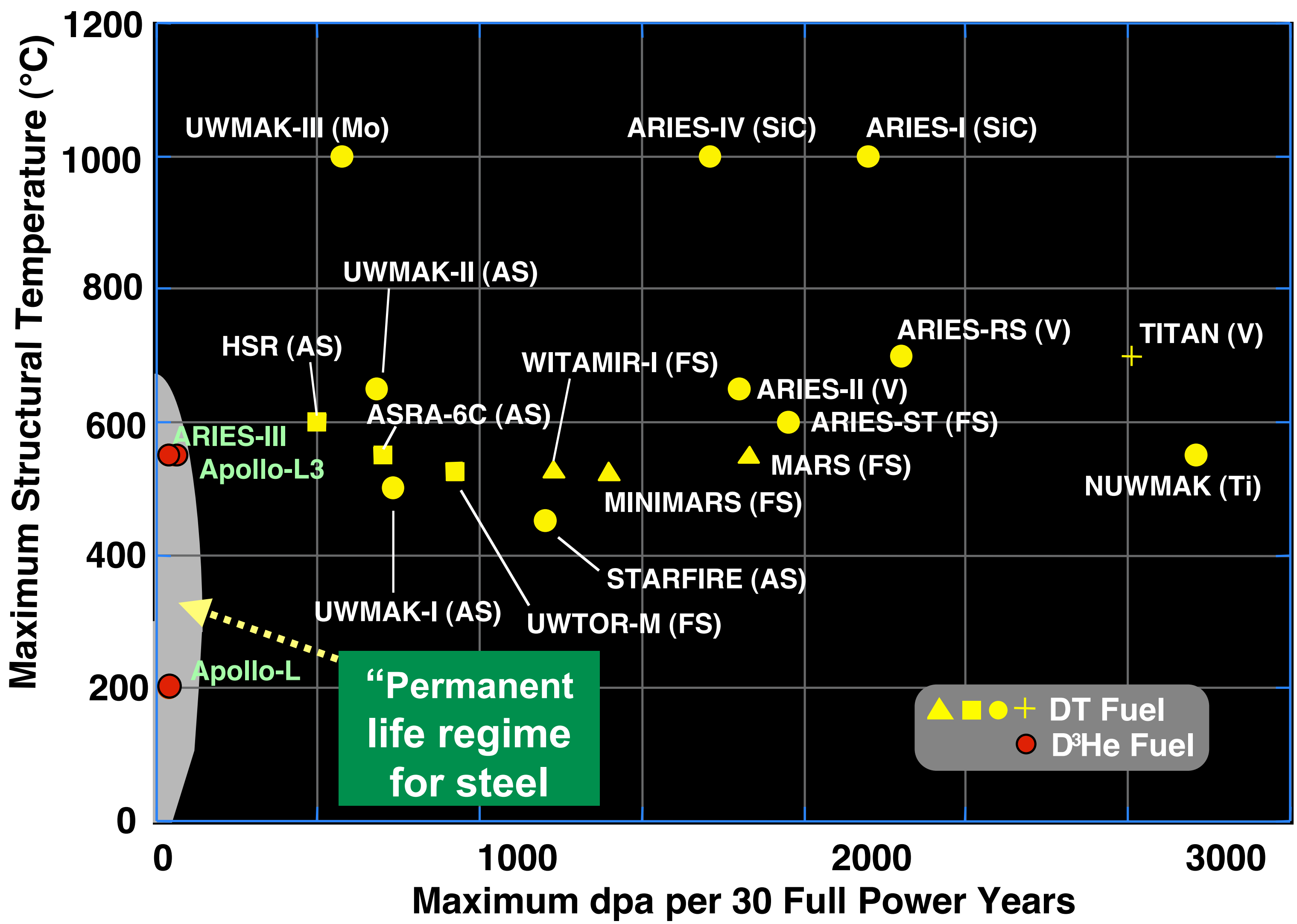
Direct Conversion to Electricity Can Give 60-80% Efficiency

- Experiment and theory agreed within 2%.

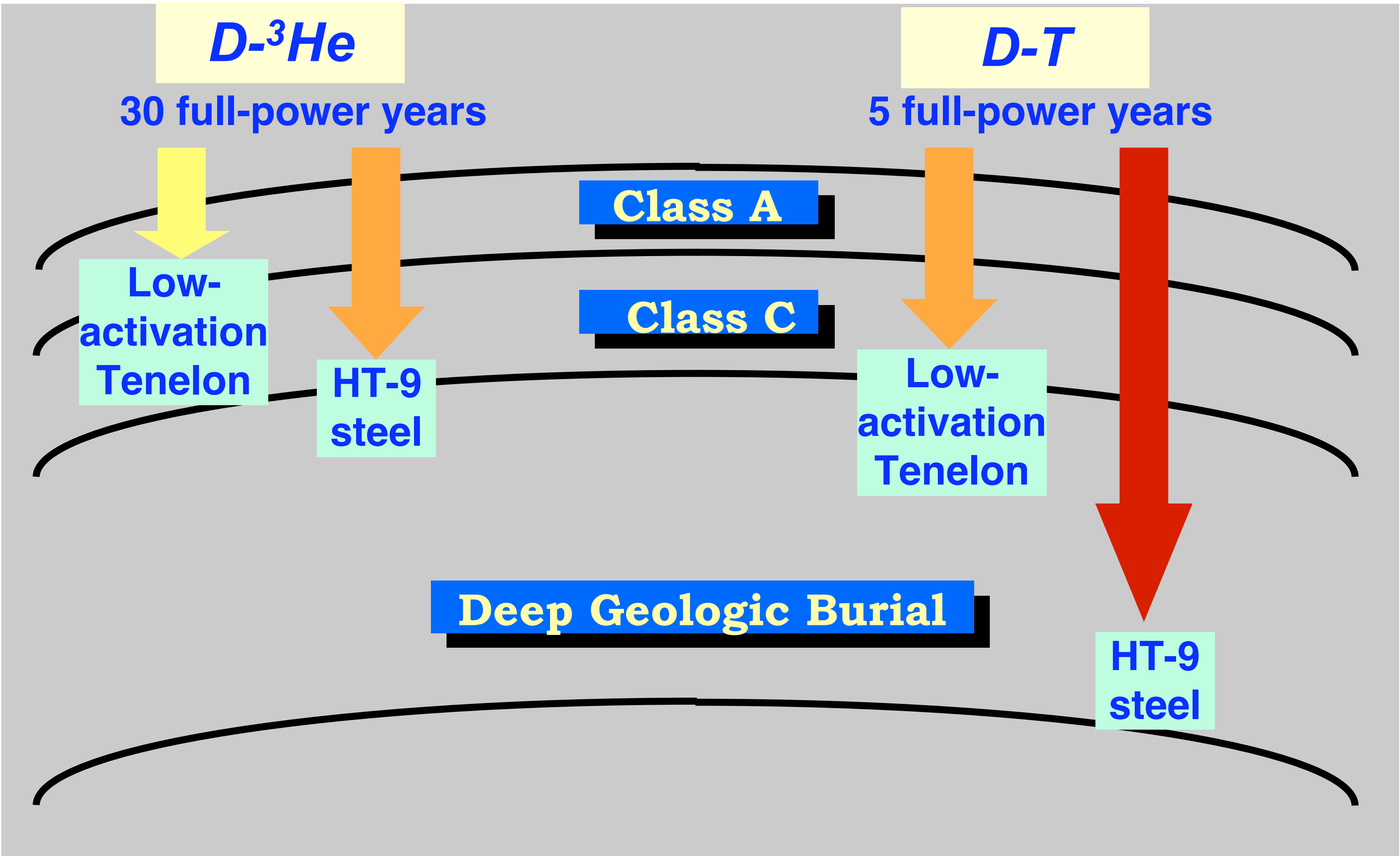
Barr-Moir experiment, LLNL
(*Fusion Technology*, 1973)



The Low Radiation Damage in D-^{3}He Reactors Allows Permanent First Walls and Shields to be Designed



Radioactive Waste Disposal is Much Easier for D-3He Reactors than for D-T Reactors



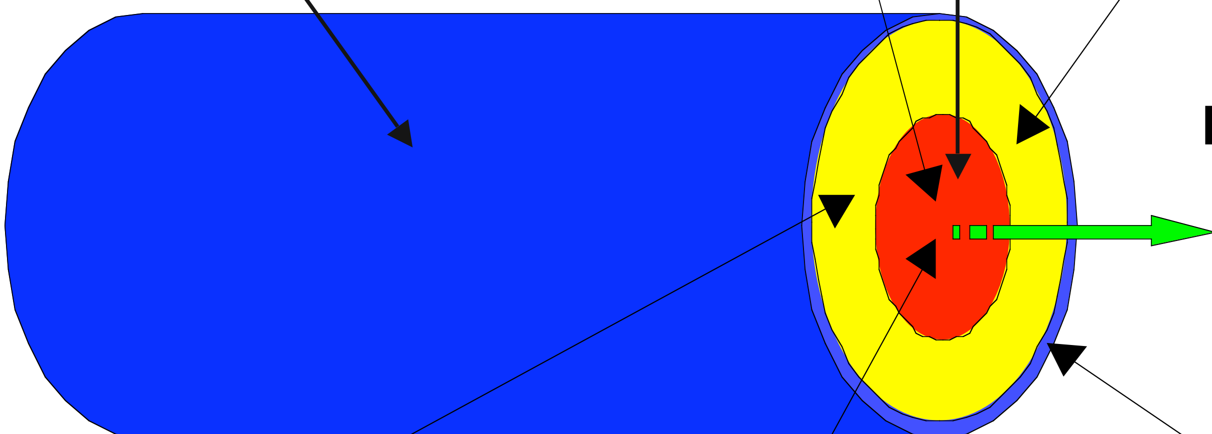
Proliferation-Resistant D-^{3}He Power Plant May Be Possible

D-^{3}He fuel for low neutron wall loading

D-^{3}He proton gyroradius contributes to stability

High-β for high fusion power density

Minimal radiation shield to reduce space for D-T shielding



Direct converter for increased electric power per unit fusion power

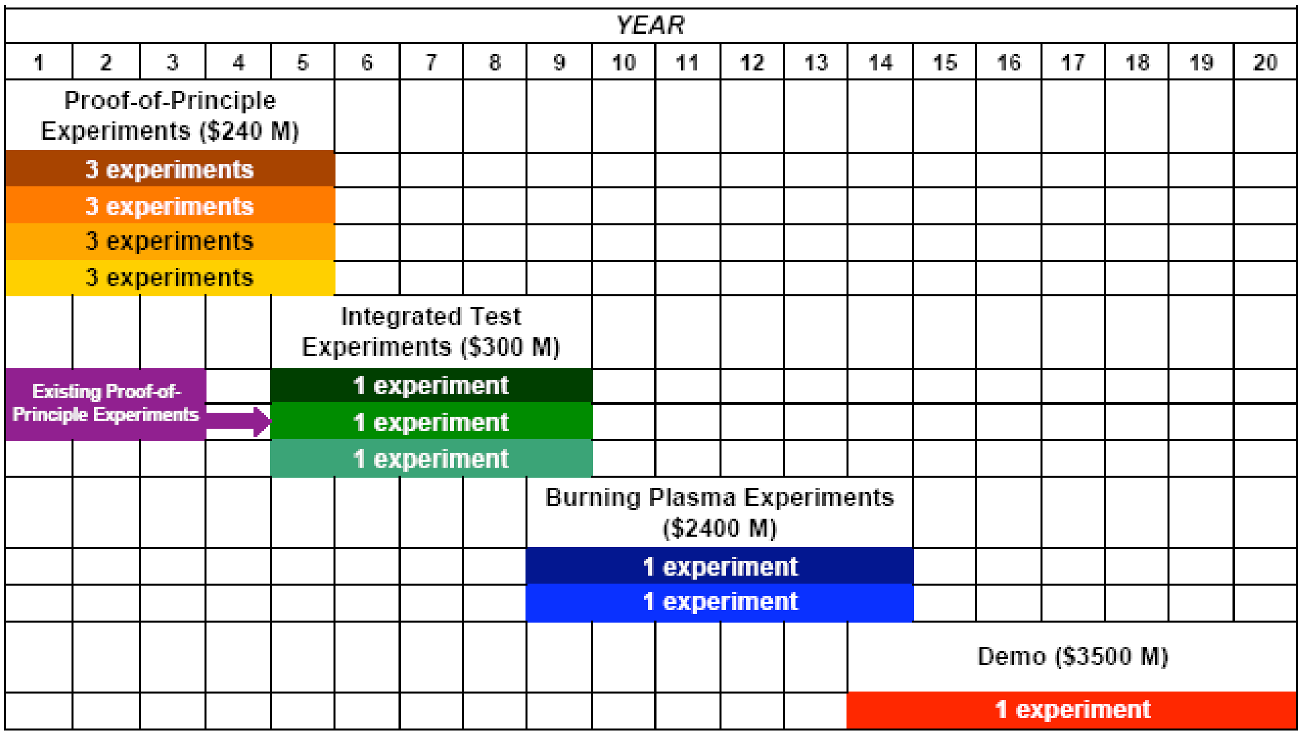
Organic coolant to make high-flux D-T operation difficult.

Small plasma to reduce space for D-T shielding

Superconducting, high-field magnet for high fusion power density

Focused R&D Could Develop D-^{3}He Fusion Quickly, *If* the Will Exists

- In parallel, experiment on several concepts with multiple devices.
  - Winnow.
  - Provide substantial power and diagnostic capabilities.
- Incorporate existing terrestrial fusion research program where possible.



- Total program cost ~ 6 B$; $10B with contingency.

Broader Perspectives

- Nuclear power in all controlled forms possesses some advantages over burning fossil fuels.
- In the context of the energy big-picture, either D-T or D-^{3}He fusion development costs would be a small fraction of the cost of a Middle-East war.
- True energy dependence would derive from D-^{3}He fusion.

Conclusions

- Burning $D\text{-}^3He$ fuel requires substantial, continued progress in plasma physics and high-β concepts.
- $D\text{-}^3He$ fusion's attractive engineering, safety, and environmental characteristics should dramatically shorten its development path if the already impressive plasma physics progress continues.
- ^3He fuel for this century must come from the Moon, but Solar-System ^3He resources are essentially inexhaustible.

References

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