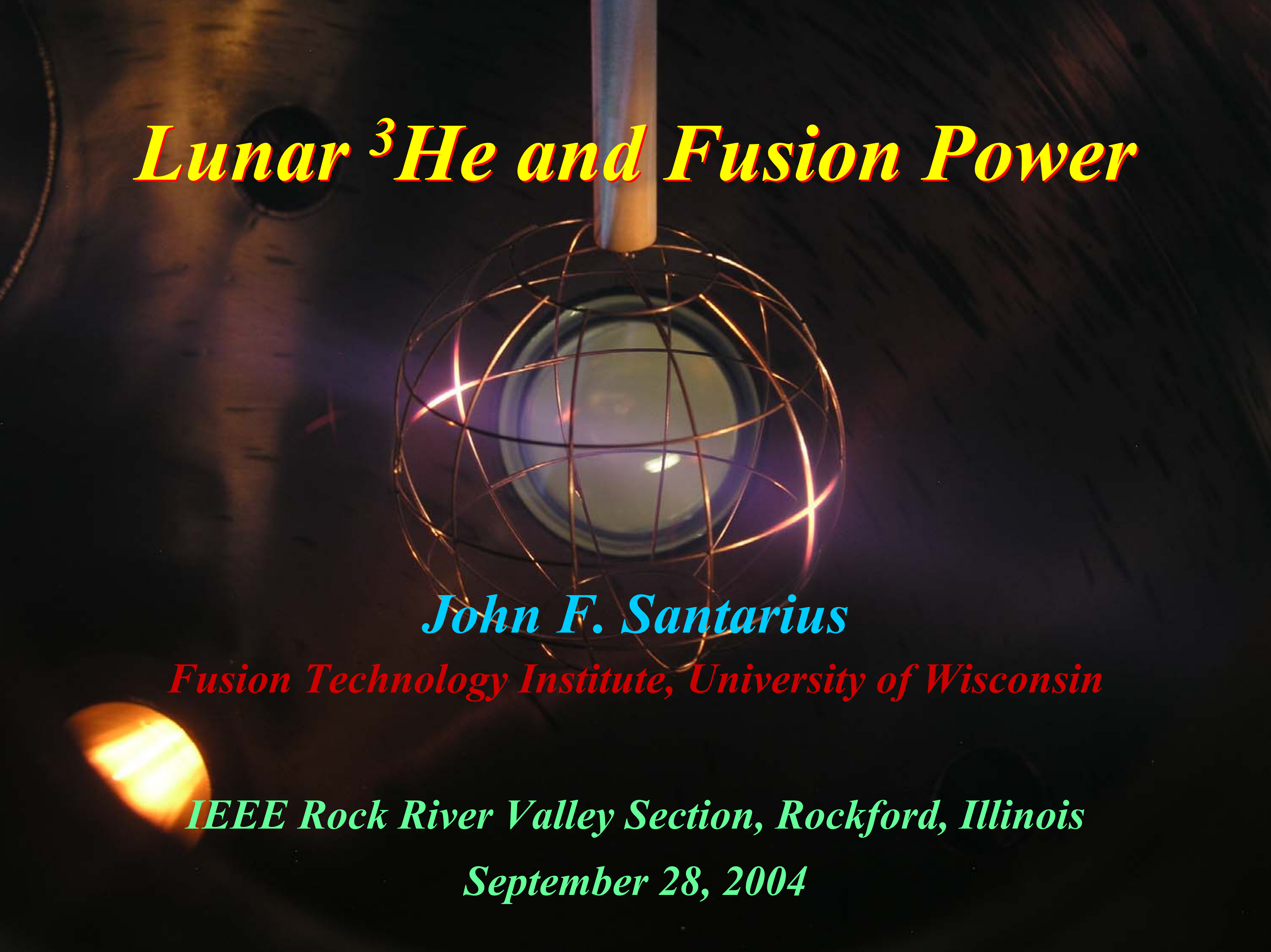


Lunar ^{3}He and Fusion Power

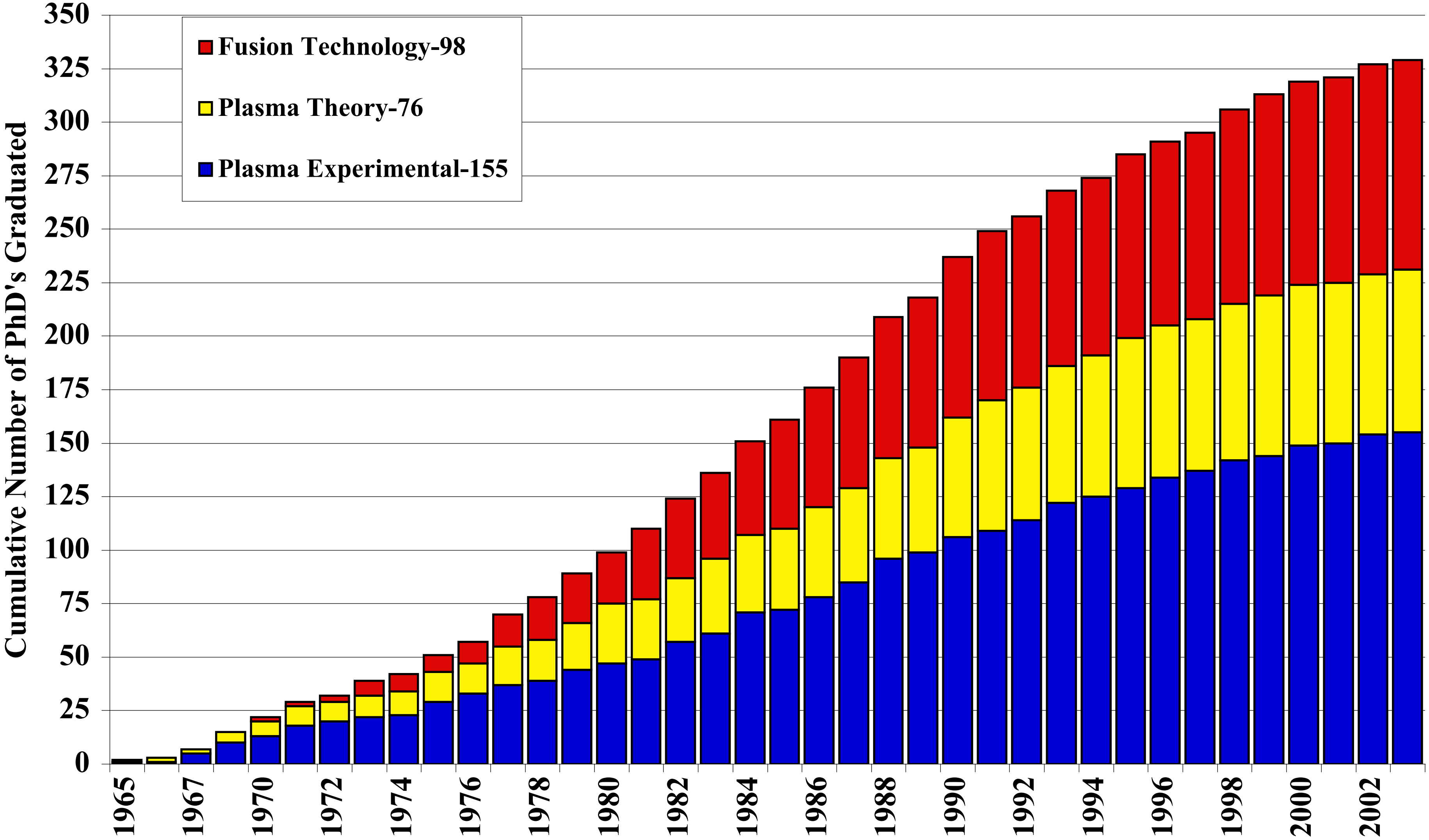
John F. Santarius

Fusion Technology Institute, University of Wisconsin

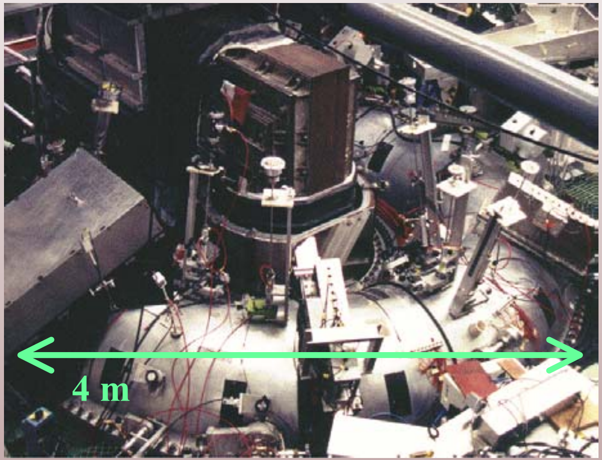
IEEE Rock River Valley Section, Rockford, Illinois

September 28, 2004

The Rate of Fusion Related PhD's Graduated From the University of Wisconsin is 1/3 of that in the 1980's

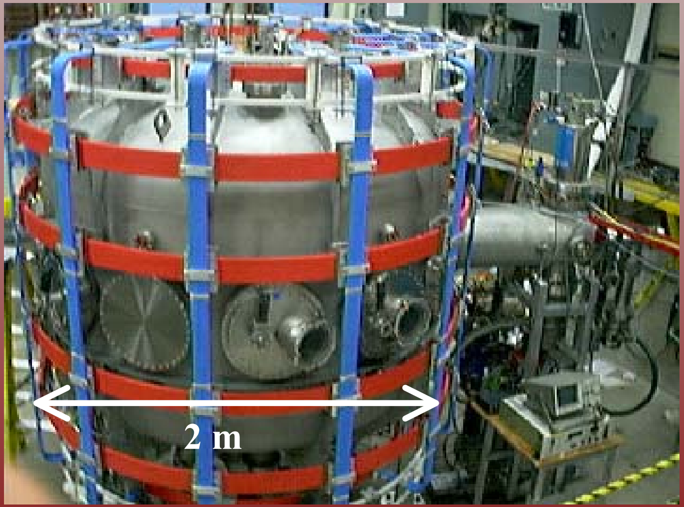


UW Investigates Several Fusion Configurations



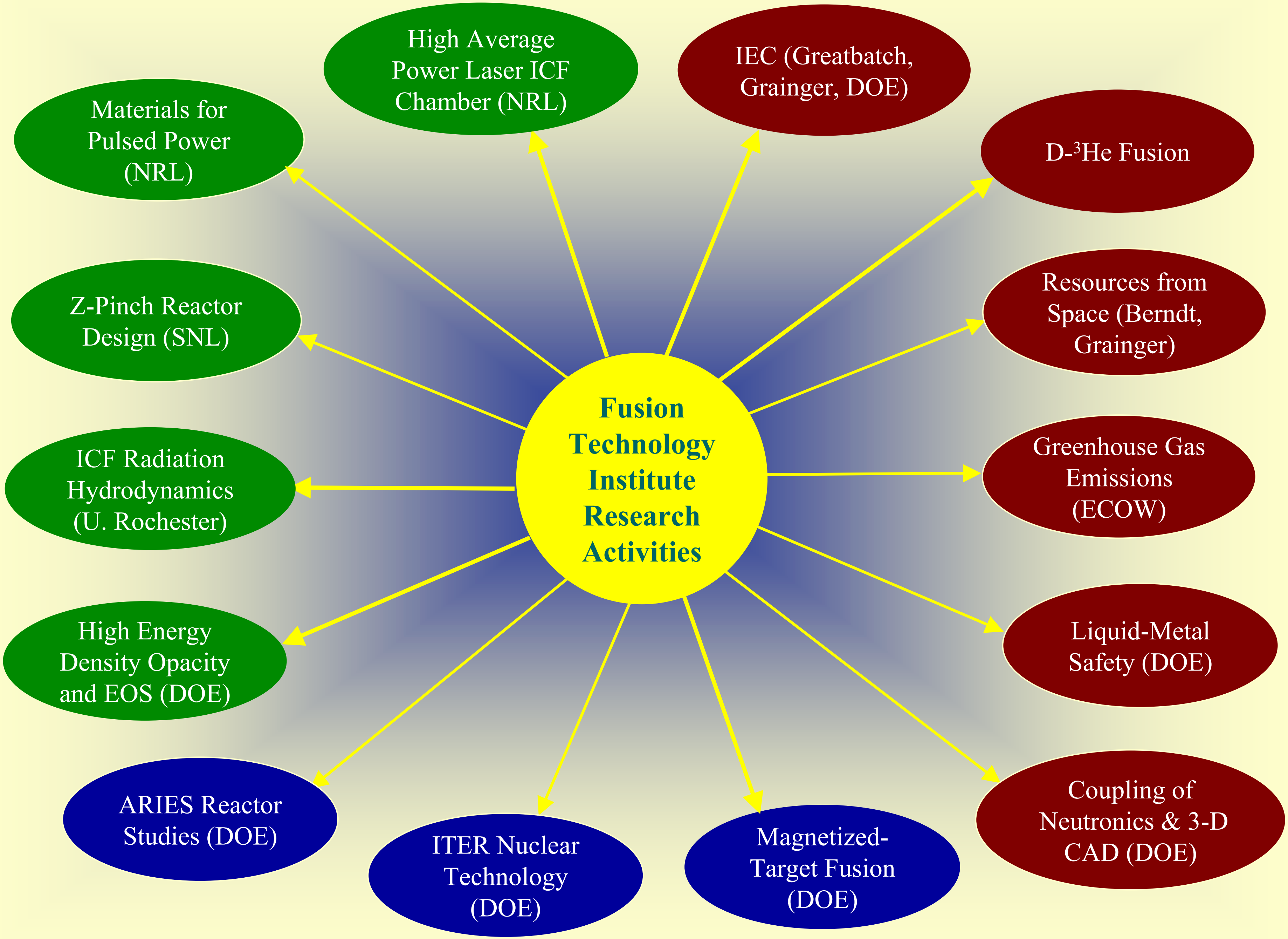
***MST* – Physics**

***HSX* - Electrical & Computer Engineering**



***Pegasus* - Engineering Physics**

***IEC* - Engineering Physics**



Fusion Technology Institute Research Activities

Materials for Pulsed Power (NRL)

High Average Power Laser ICF Chamber (NRL)

IEC (Greatbatch, Grainger, DOE)

D-^{3}He Fusion

Z-Pinch Reactor Design (SNL)

Resources from Space (Berndt, Grainger)

ICF Radiation Hydrodynamics (U. Rochester)

Greenhouse Gas Emissions (ECOW)

High Energy Density Opacity and EOS (DOE)

Liquid-Metal Safety (DOE)

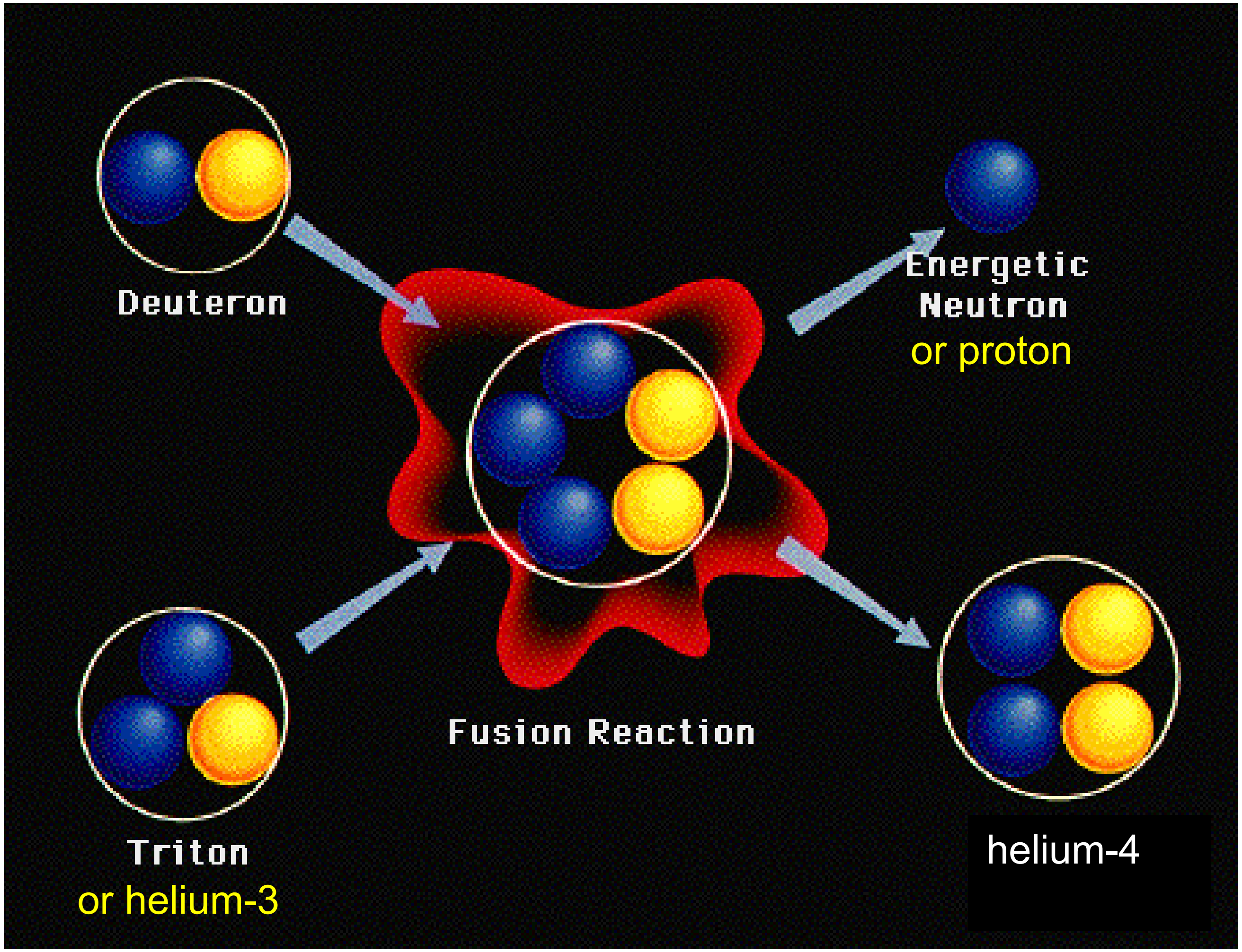
ARIES Reactor Studies (DOE)

ITER Nuclear Technology (DOE)

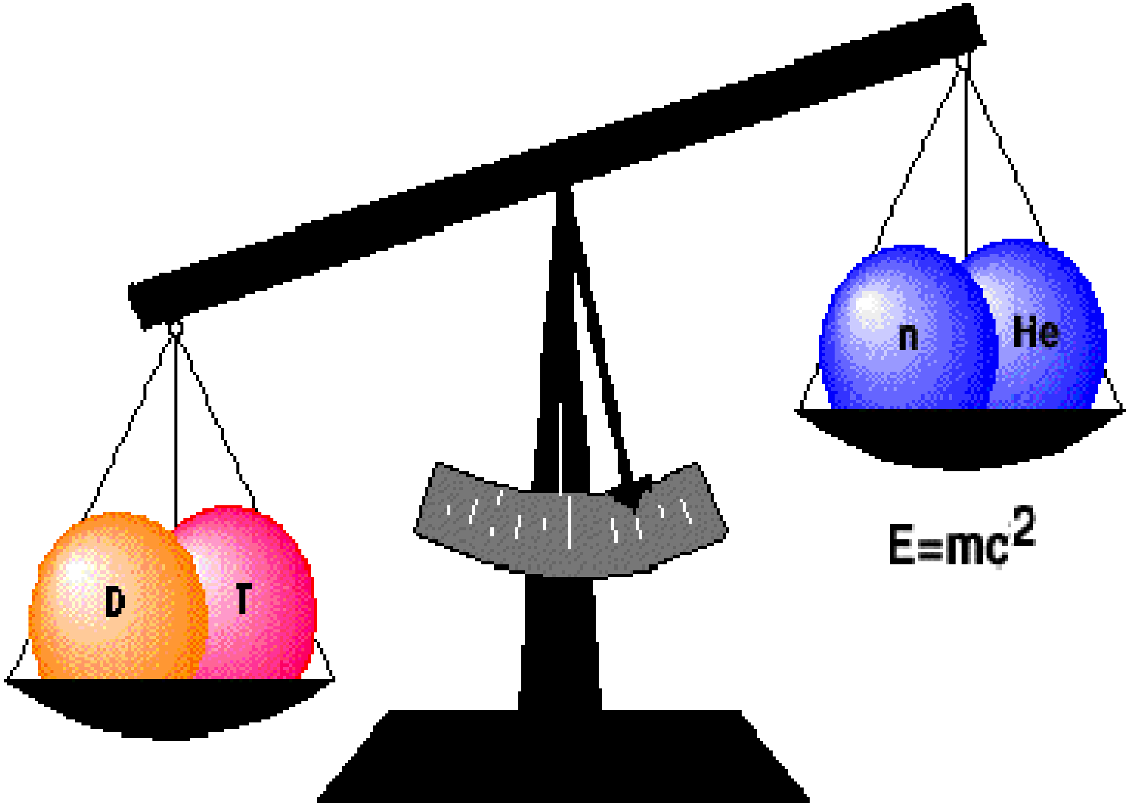
Magnetized-Target Fusion (DOE)

Coupling of Neutronics & 3-D CAD (DOE)

Fusion Combines Light Isotopes to Create Other Particles



Fusion Converts Mass into Energy



"Advanced" Fusion Fuels Face a More Difficult Physics Development Path than D-T Fuel

1st generation fuels:

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

D + D → n (2.45 MeV) + ^{3}He (0.82 MeV)
→ p (3.02 MeV) + T (1.01 MeV)
{50% each channel}

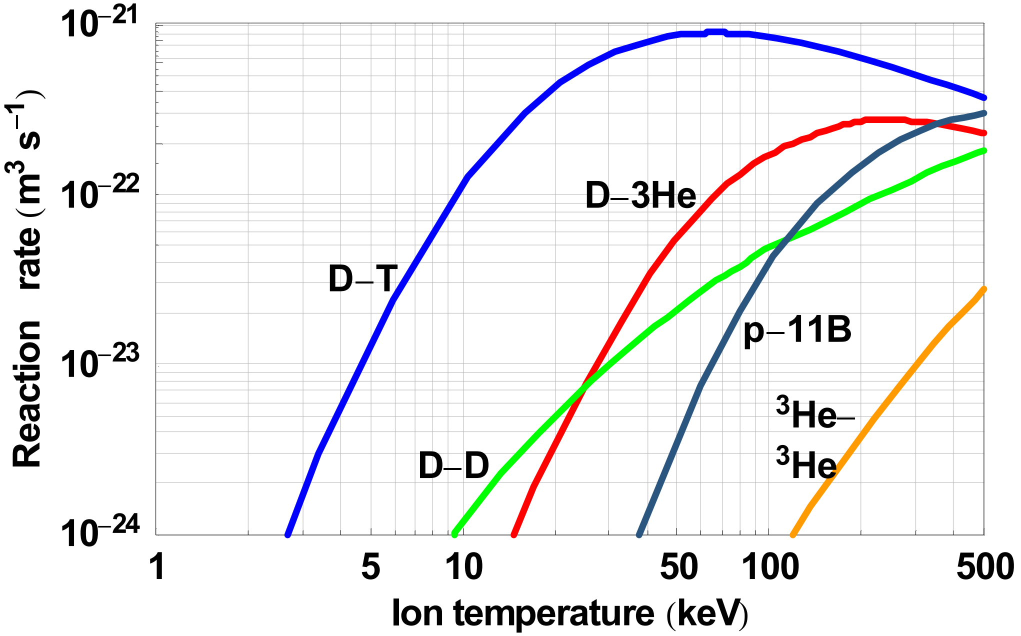
2nd generation fuel:

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

3rd generation fuels:

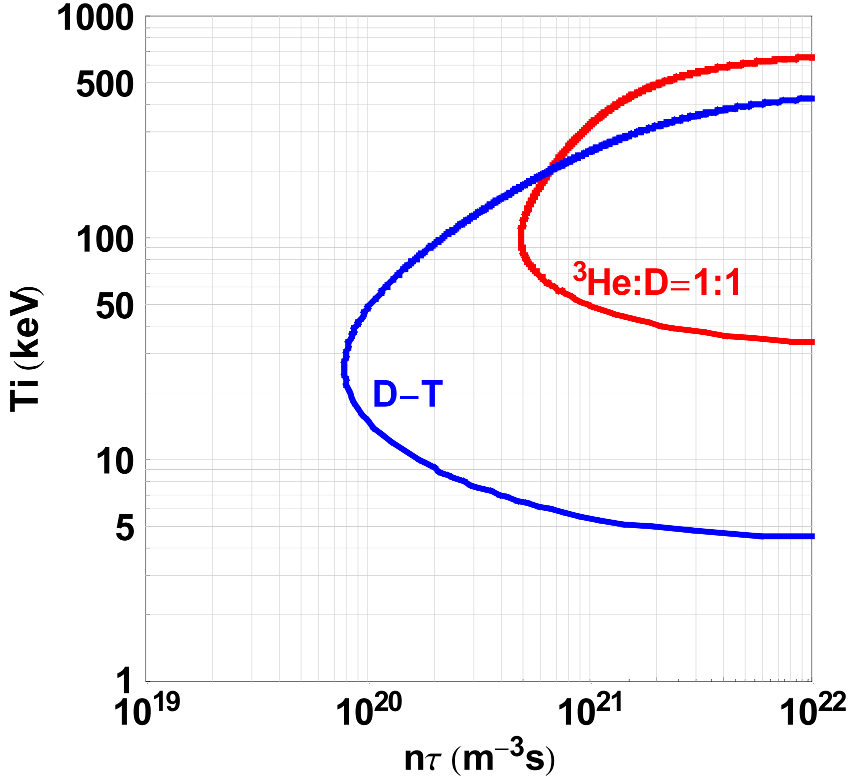
^{3}He + ^{3}He → 2 p + ^{4}He (12.86 MeV)

p + ^{11}B → 3 ^{4}He (8.68 MeV)

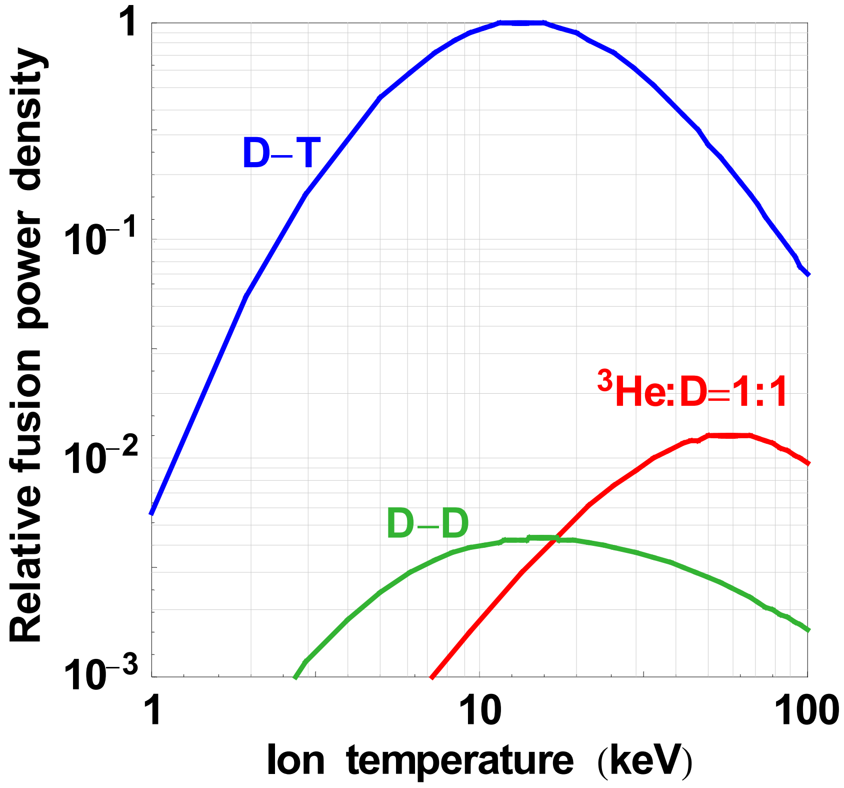


D-^{3}He Fuel Faces Larger Physics Obstacles than D-T

Ignition contours against bremsstrahlung



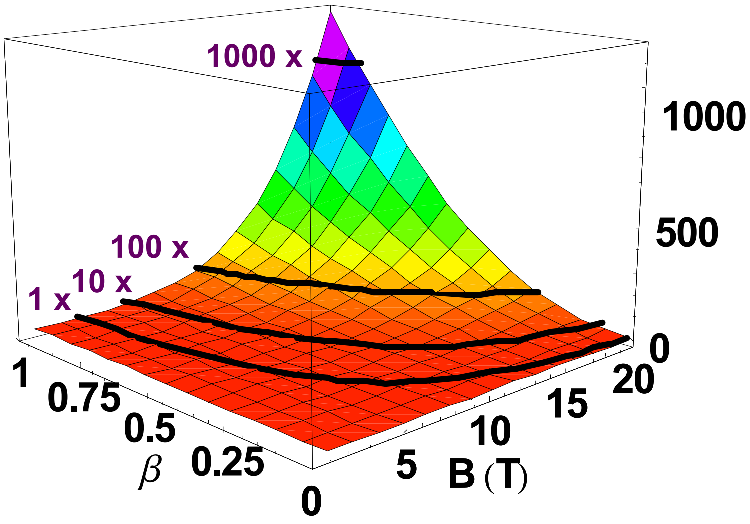
Power density



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

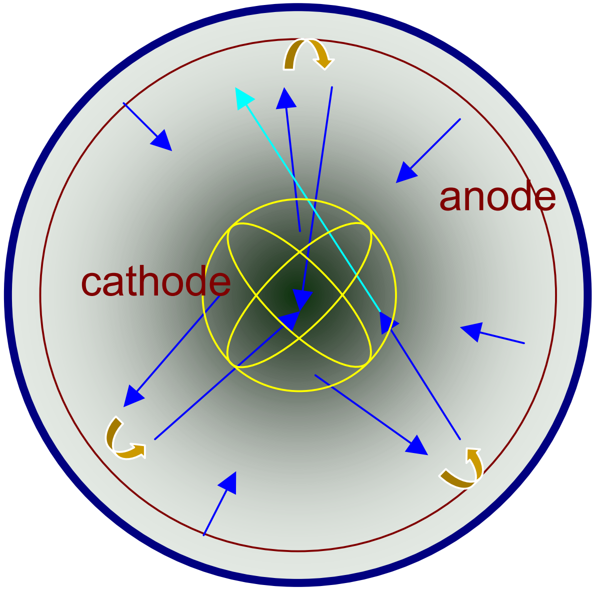
- D-T fueled innovative concepts become limited by first-wall neutron or surface heat loads well before they reach β (=plasma pressure/B-field pressure) or B-field limits.
- D-T fueled tokamaks (β~5%) optimize at B ~ 15 T.
- D-^{3}He needs a factor of ~80 above D-T fusion power densities.
  - Superconducting 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.

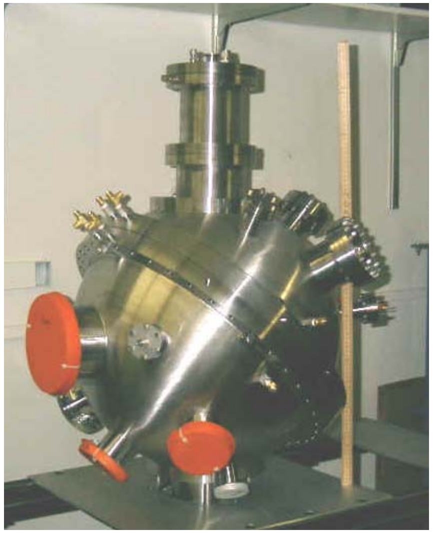
Power Density Relative to a D–T Tokamak with β=5% and B=15 T



Inertial-Electrostatic Fusion Depends on Creation of a Radial Electrostatic Well and Spherically (or Cylindrically) Convergent Ion Flow

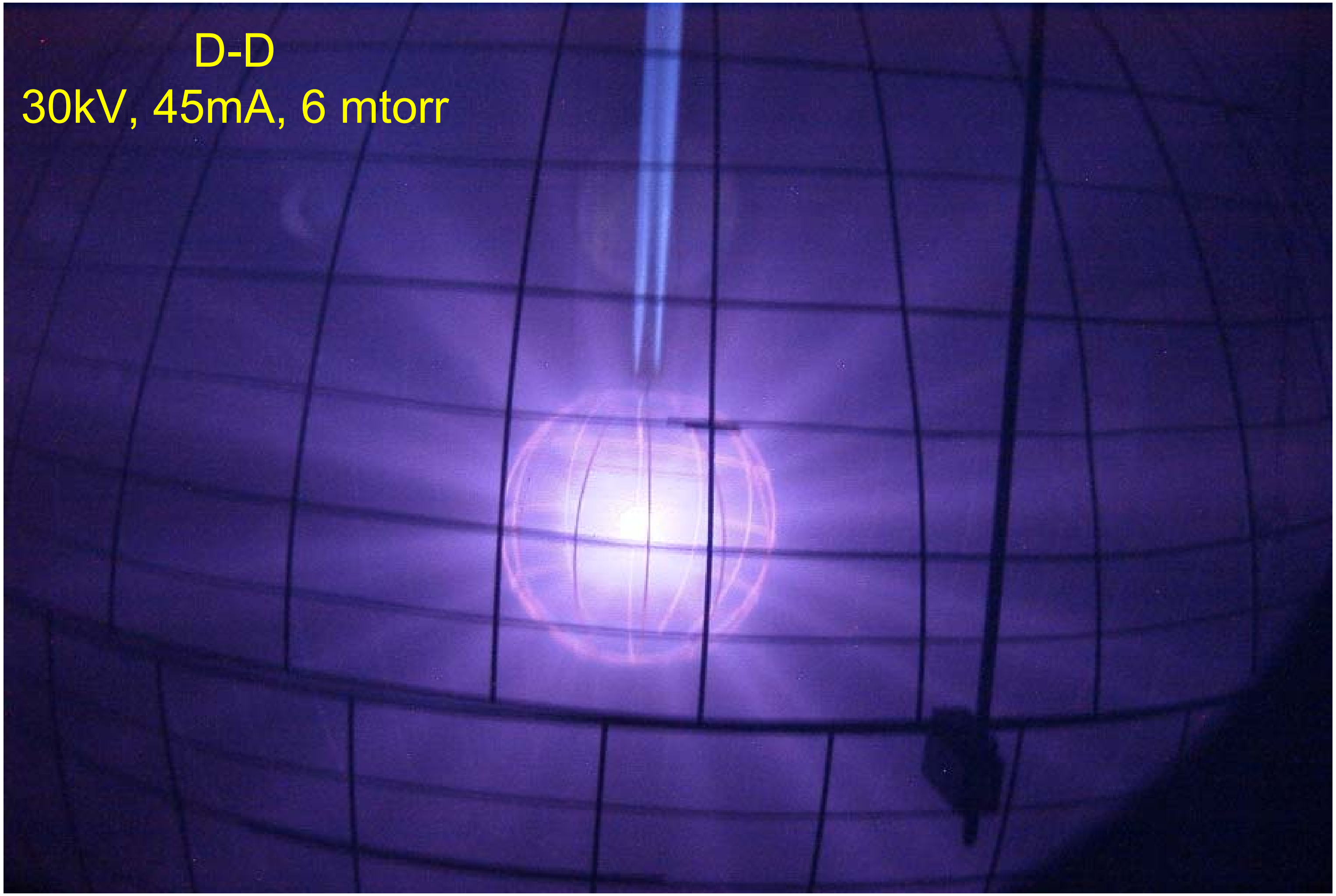
1. Inner grid (cathode) is biased to a high negative potential.
2. Fuel gas flows into the chamber and pressure is maintained.
3. Positive ions are created around the outer grid (anode).
4. Ions accelerate toward inner grid, gaining fusion-relevant energies.
5. Ions and electrons ionize neutral gas.





5. Ions charge-exchange with neutrals, fuse with other ions or neutrals, or hit grids.
6. Charge-exchange neutrals fuse with background gas.
7. Particle detectors monitor reaction rates.

Low-Voltage, High-Pressure Conditions Produce Visible Electron Jets



R.L. Hirsch and G.A. Meeks: Mid-60's Ion-Gun-Driven IEC Experiment

- Operated with D-T fuel
- Generated ~10^{10} neutrons/s

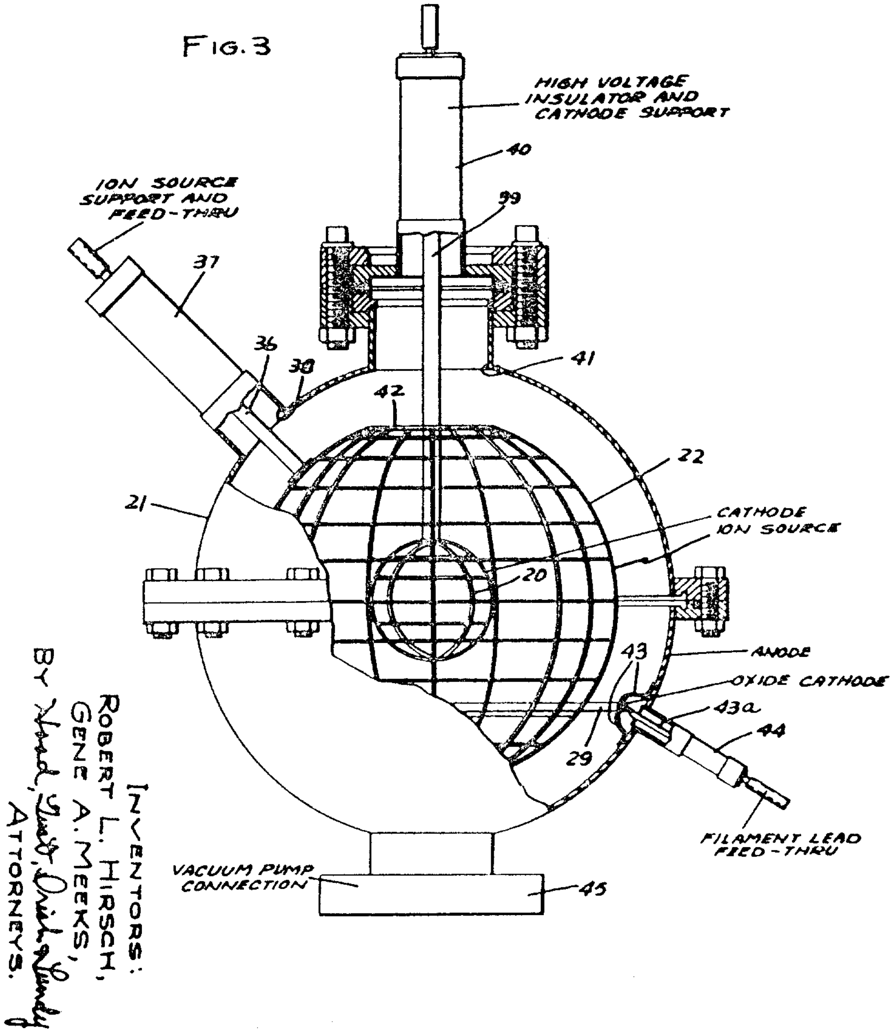
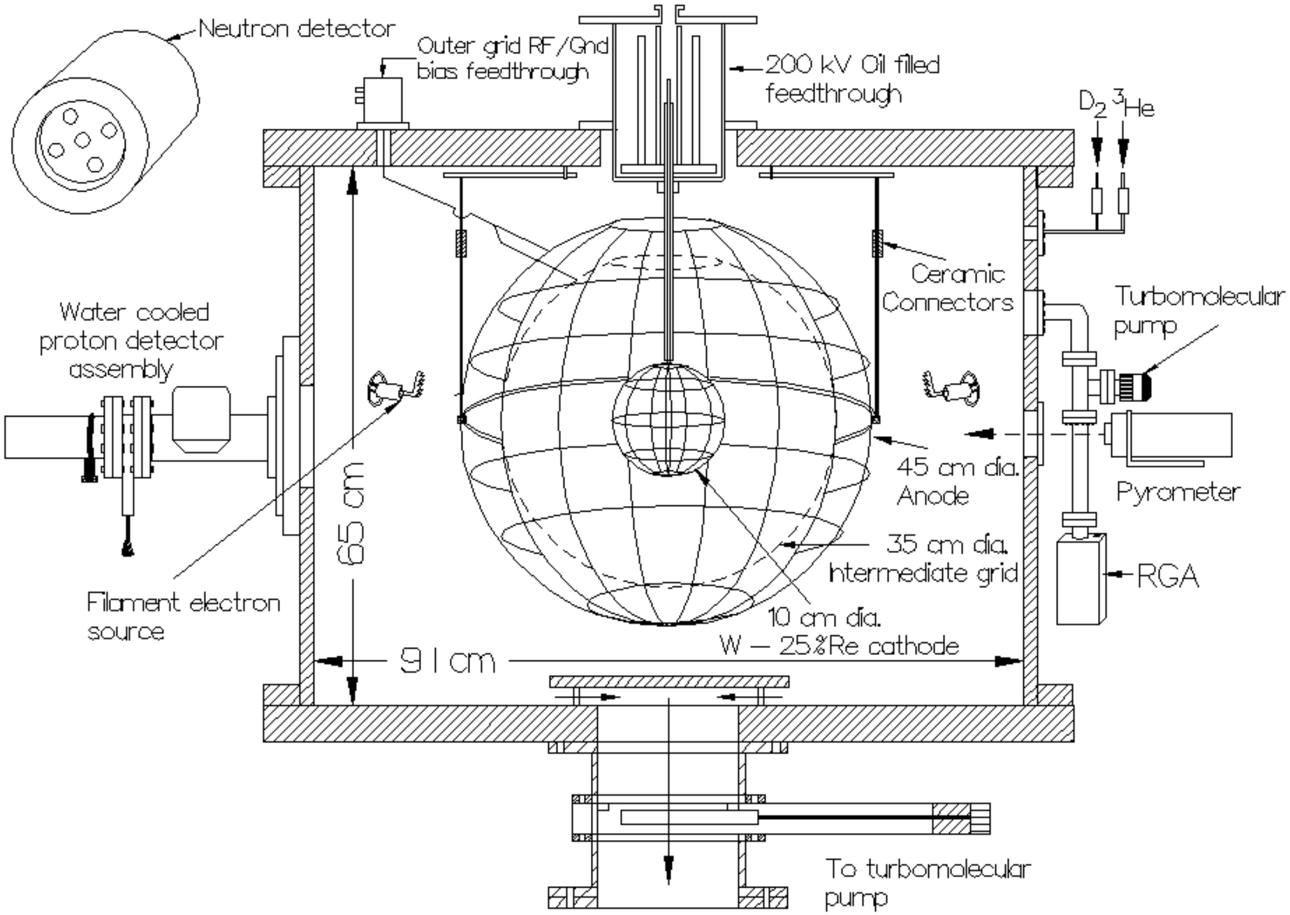
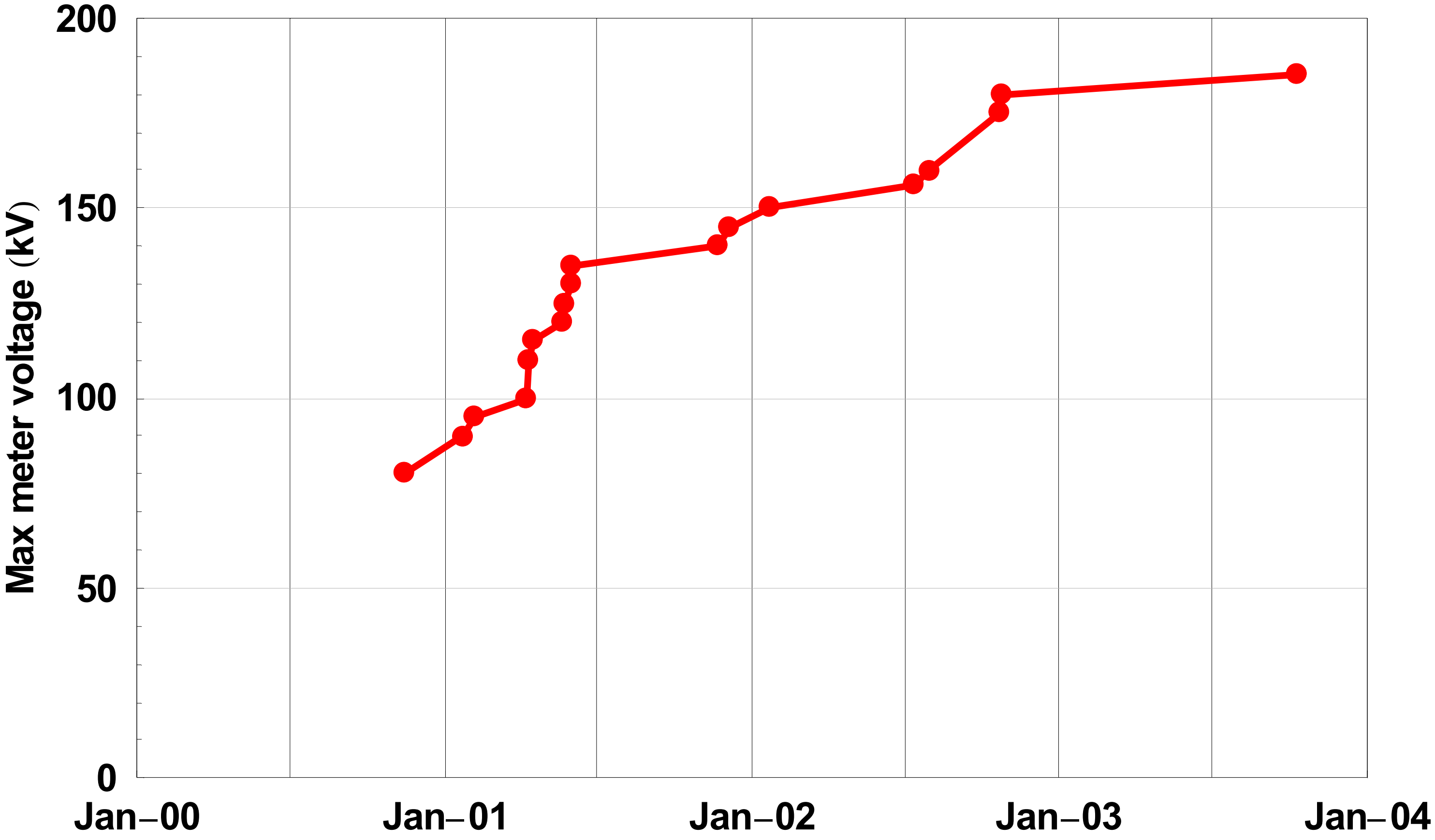


FIG. 3

Present UW Aluminum Chamber Provides a Large Volume Reaction Region



Significant Progress Has Been Made in Achieving High-Voltage Operation

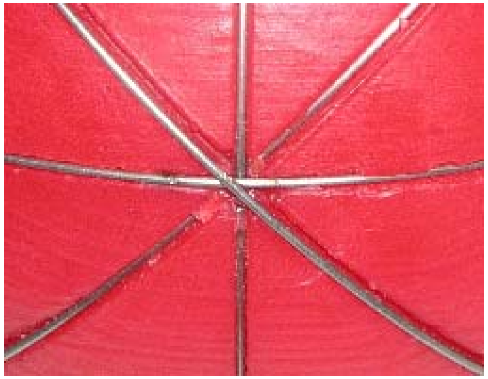


Fabrication System for Standardized Grid

1. Mold produced from rapid prototype model

2. Wax poured into mold

3. Wires wound around wax form

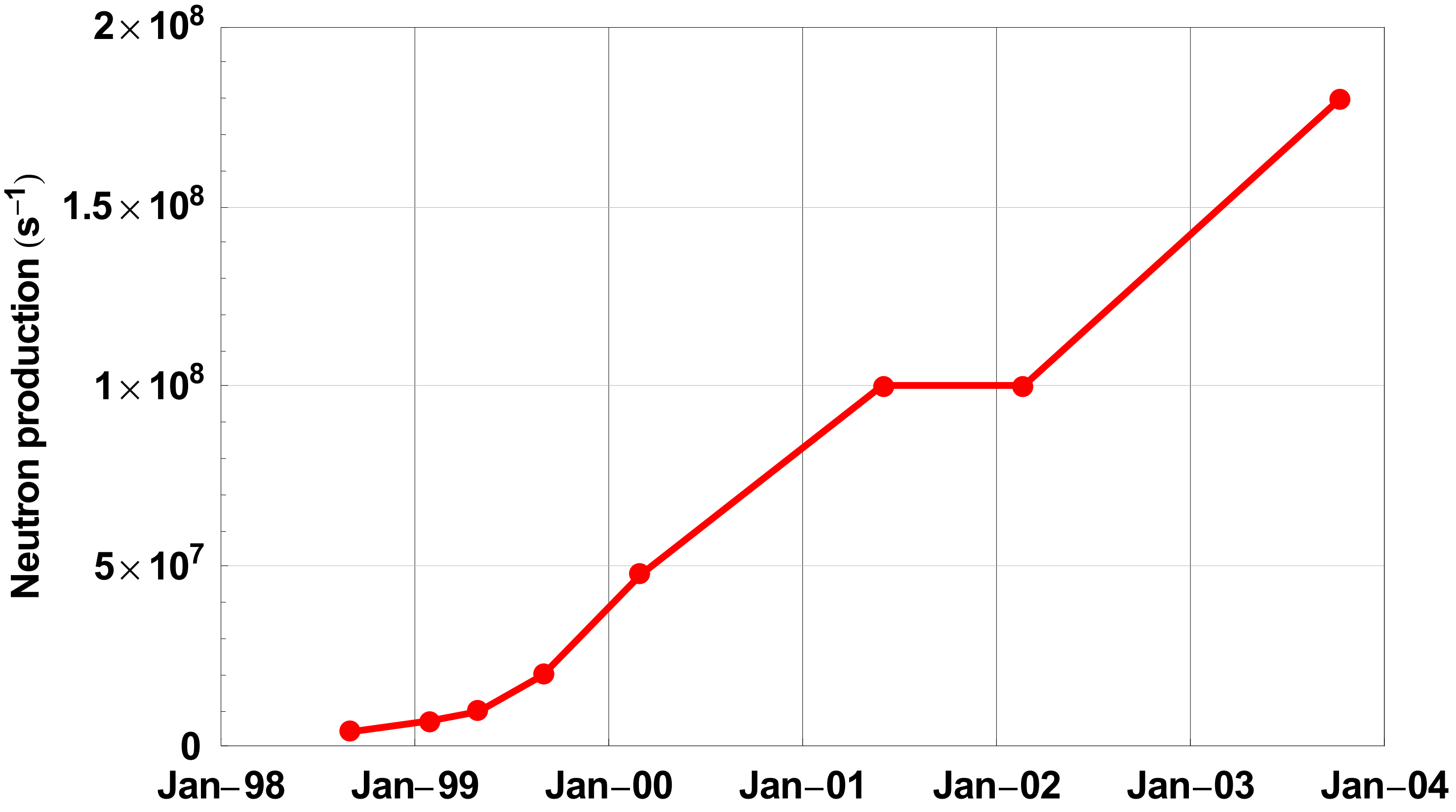


4. Wires spot welded at junctions

5. Wax form melted away at ~80 °C

6. Finished grid cathode

Maximum UW IEC D-D Neutron Production So Far is 1.8 x 10^8 per Second

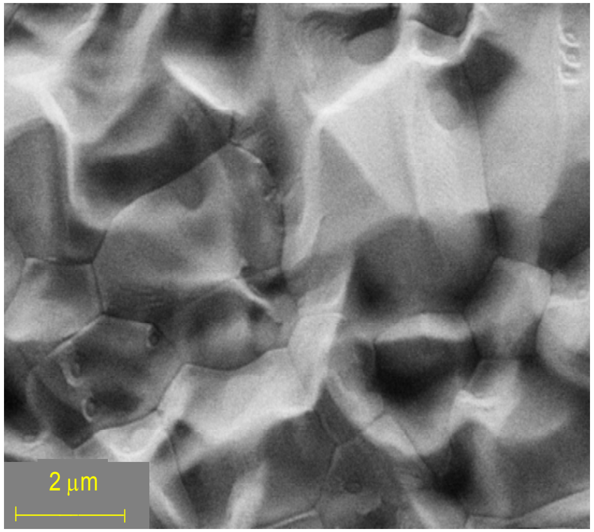


Fast He Ions Can Produce Significant Damage in Materials

Wire grid cathode was replaced by a sample target.

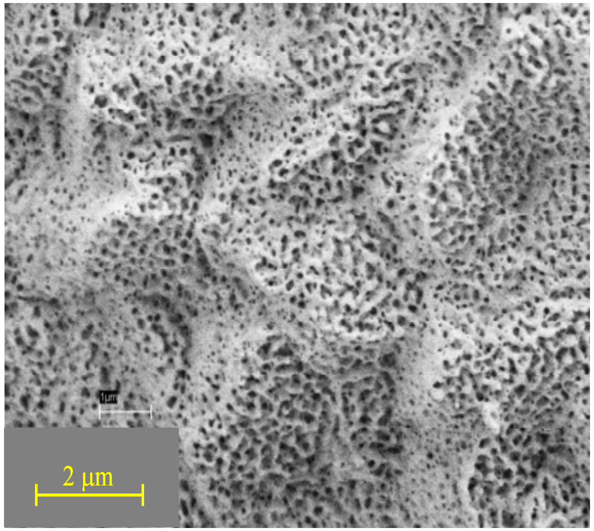
Deuterium bombardment did little damage.

TaC irradiated at 830 °C with >6x10^{17} D/cm^{2}.



Helium bombardment did significant damage.

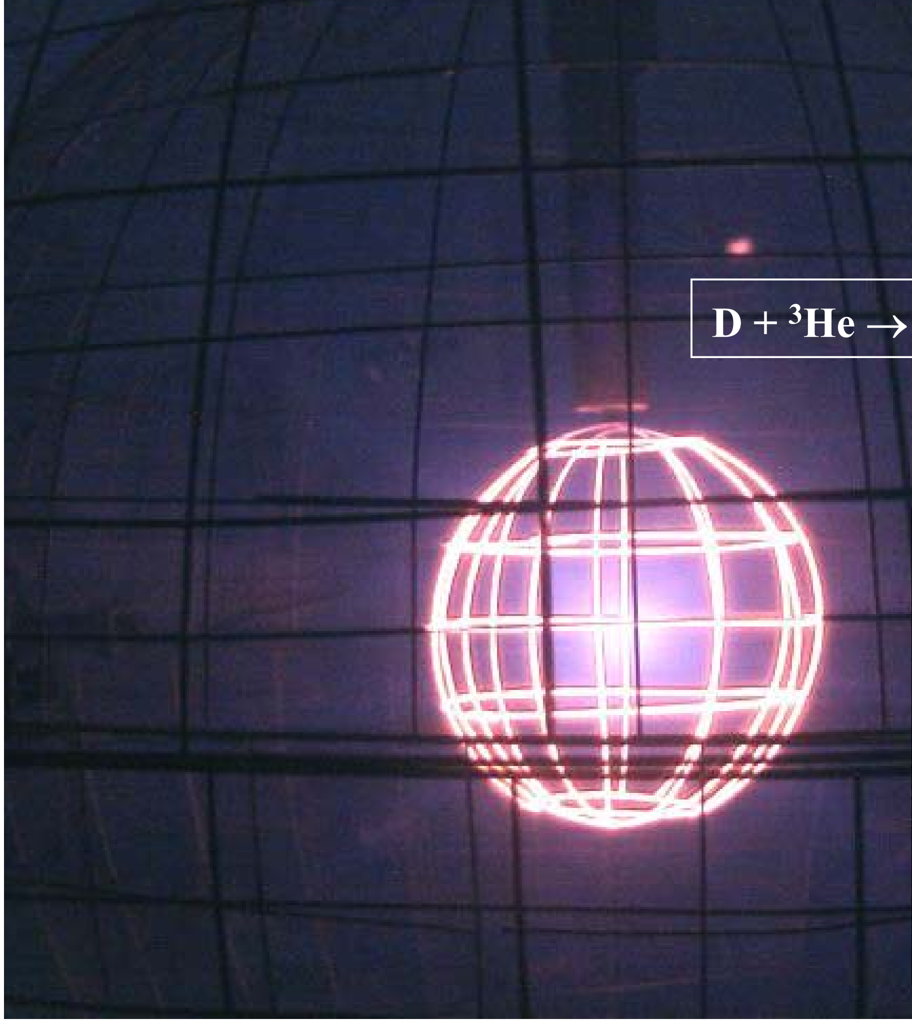
HfC irradiated at 775 °C with >6x10^{17} He/cm^{2}.



- Initial work on W by Ben Cipiti (submitted to J. Nucl. Materials, 2004).
- Presently part of Ross Radel's thesis research.

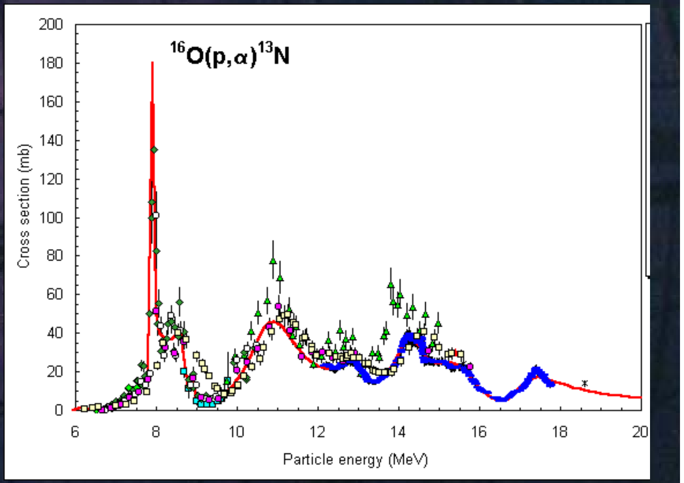
D-^{3}He Fusion Protons Can Produce Useful Radioisotopes for Nuclear Medicine

- The glowing cathode shown here is 10 cm in diameter



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

Cross sections for producing the PET-scan isotope ^{13}N



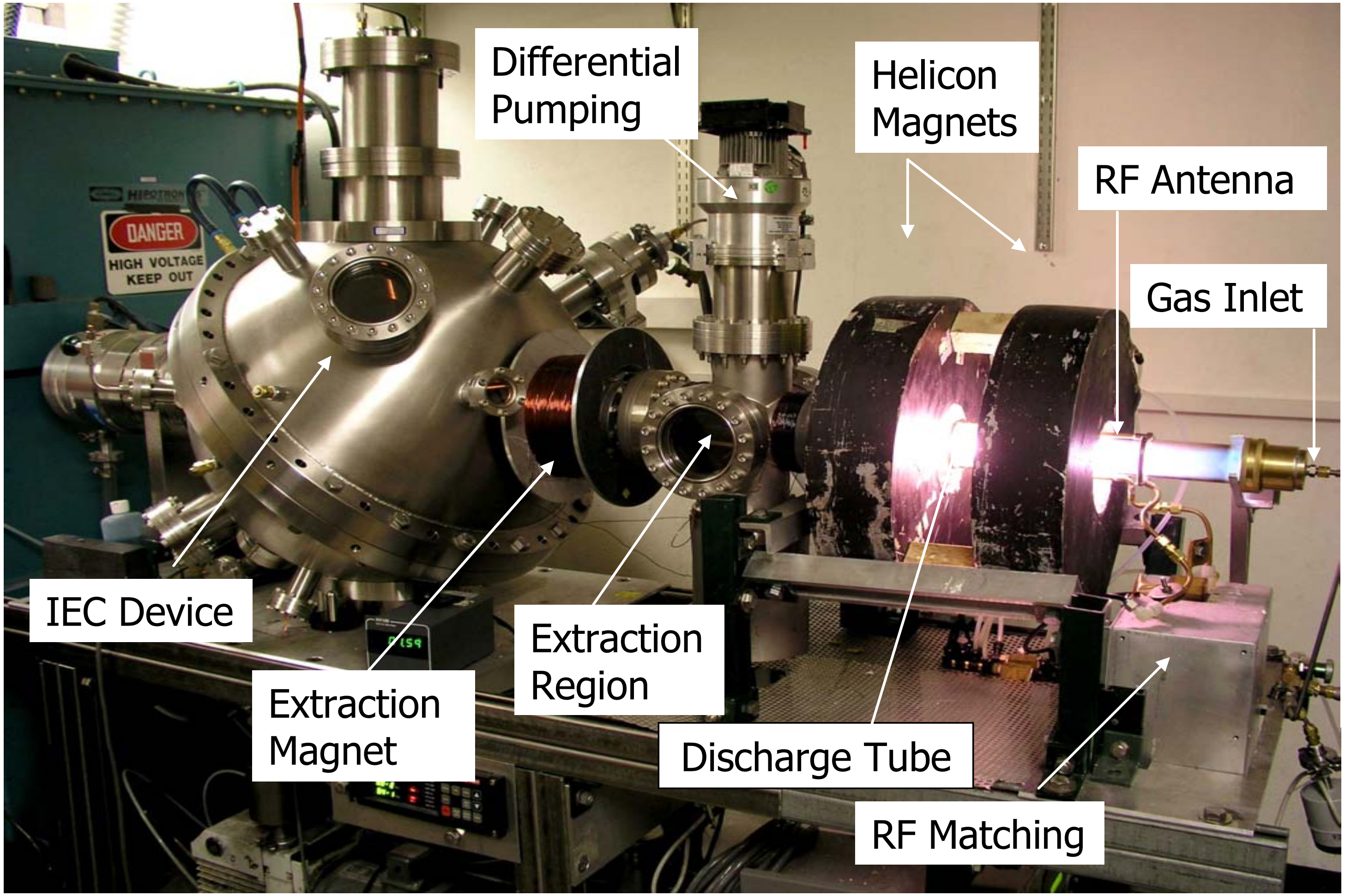
Examples of Positron Emitting Isotopes

Parent Isotope	Production Reaction	PET Isotope	Half Life
^{18}O	(p, n)	^{18}F	110 min
^{14}N	(p, α)	^{11}C	20 min
^{16}O ^{13}C	(p, α) (p,n)	^{13}N	10 min
^{15}N	(p, n)	^{15}O	2 min

UW IEC Experiments Produced ^{13}N, a Valuable PET-scan Radioisotope

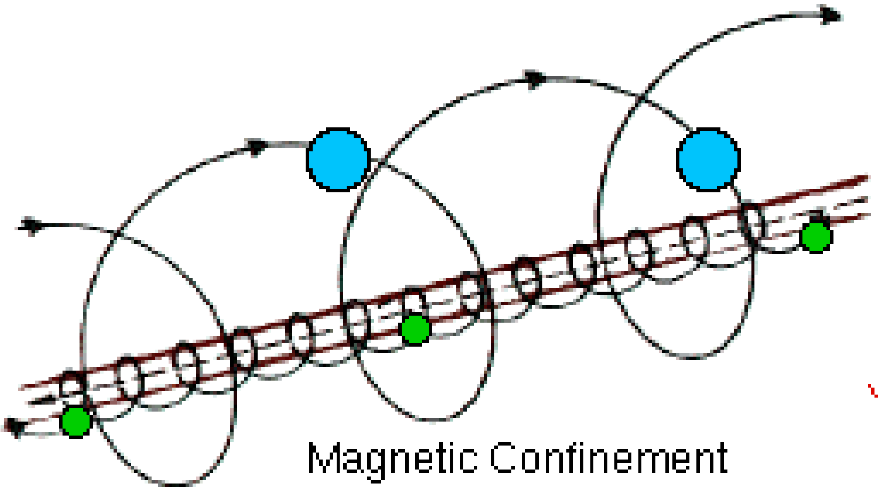
John Weidner

Helicon Ion Source Operating with UW's Spherical IEC Chamber

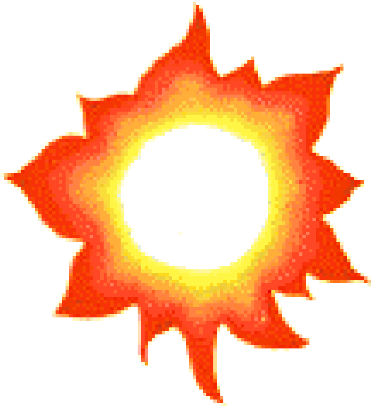


- Thesis research by Greg Piefer

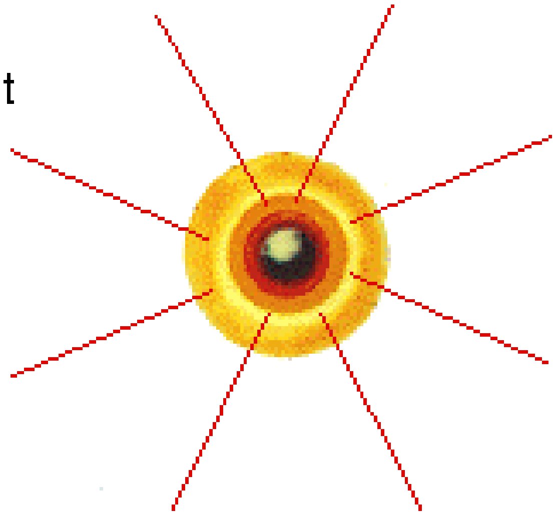
Fusion Can Be Accomplished in Several Ways



Magnetic Confinement

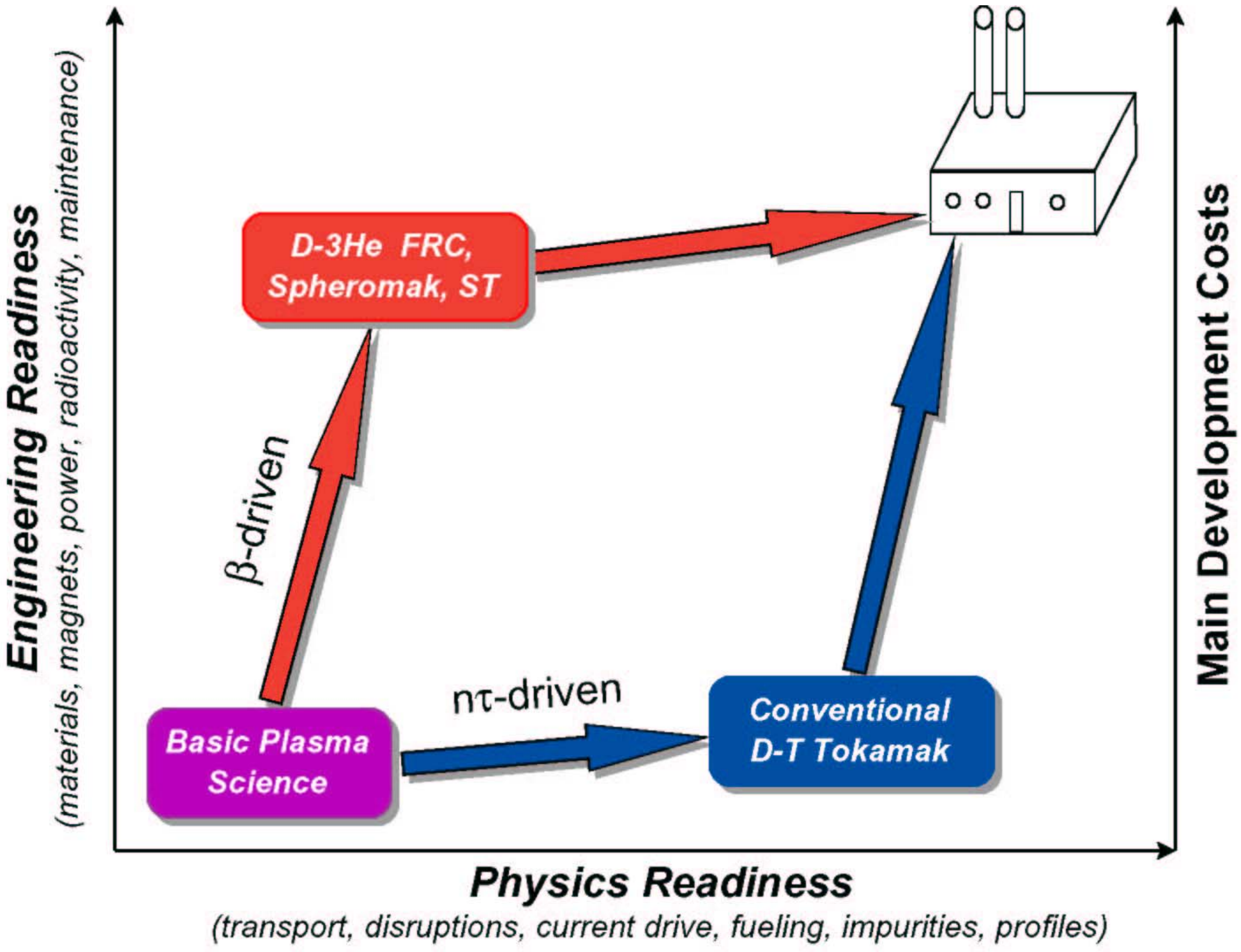


Gravitational Confinement
in the Sun and Stars



Inertial Confinement
Using Lasers

D-^{3}He Fuel Will Lower Development Costs



Engineering Readiness

(materials, magnets, power, radioactivity, maintenance)

D-3He FRC, Spheromak, ST

β-driven

Basic Plasma Science

nτ-driven

Conventional D-T Tokamak

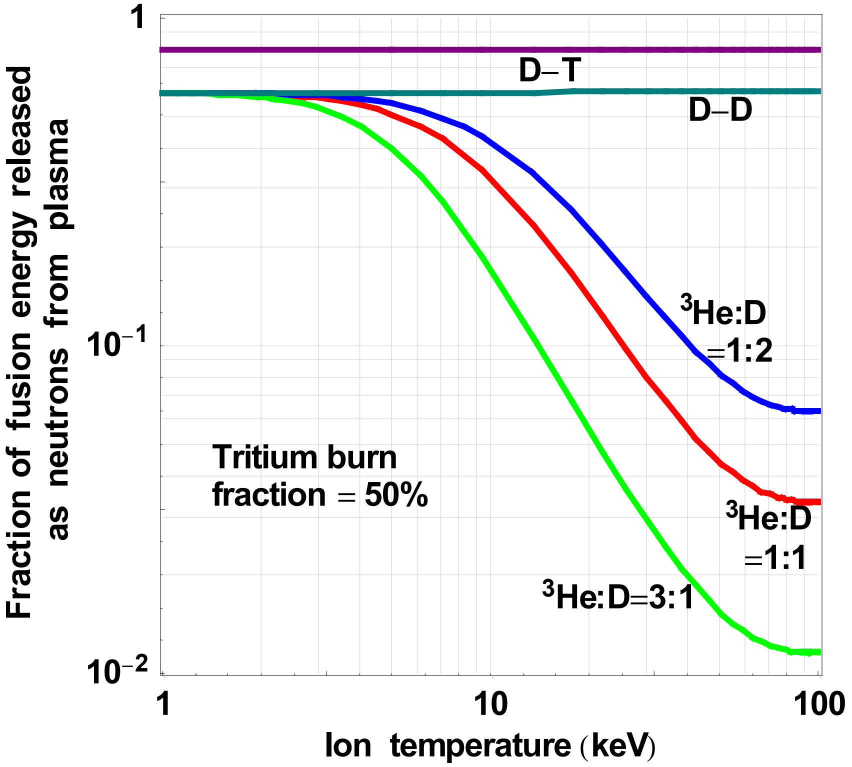
Main Development Costs

Physics Readiness

(transport, disruptions, current drive, fueling, impurities, profiles)

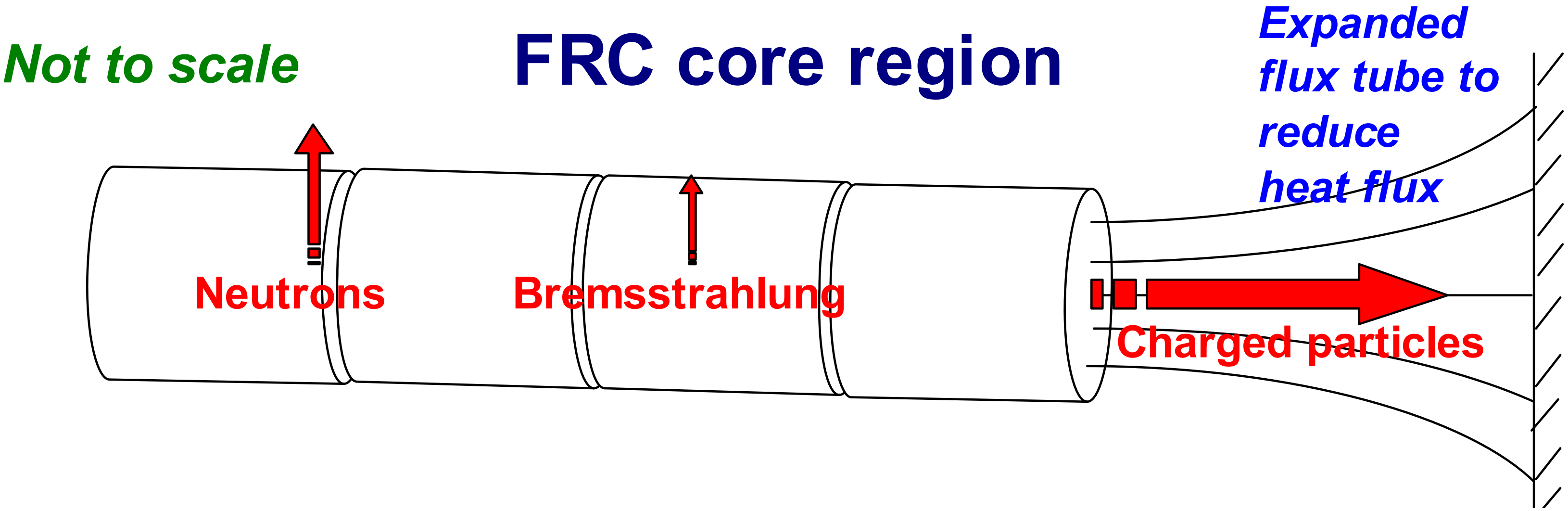
D-^{3}He Fuel Generally Gives Easier Engineering and Safety

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

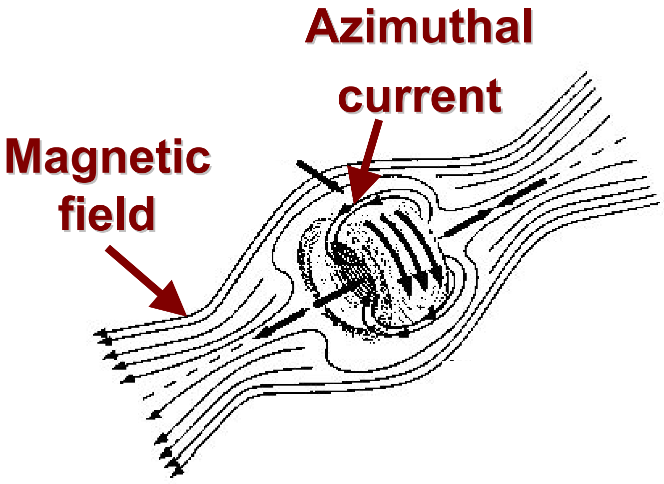


Linear Geometry Provides Solution to Handling Charged-Particle Surface Heat Flux

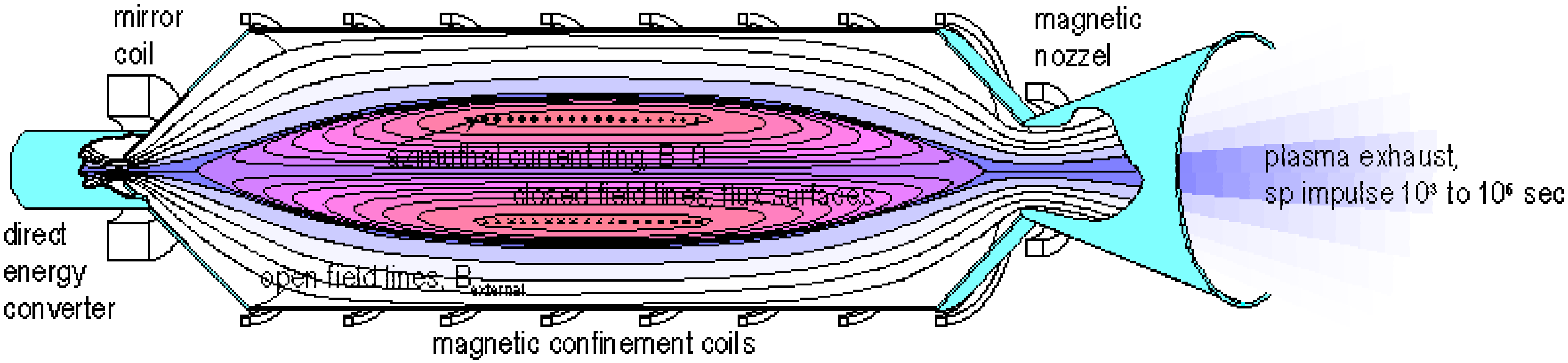
- Charged-particle power transports from internal plasmoid (in an FRC or spheromak) to edge region and then out ends of fusion core.
- Expanded flux tube in end chamber reduces heat and particle fluxes, so charged-particle transport power only slightly impacts the first wall.
- Mainly bremsstrahlung power contributes to first-wall surface heat.
  - Relatively small peaking factor along axis for bremsstrahlung and neutrons.
- High power density does not necessarily imply unmanageable first-wall heat flux.



Field-Reversed Configuration (FRC) Would Be Attractive for Fusion Power



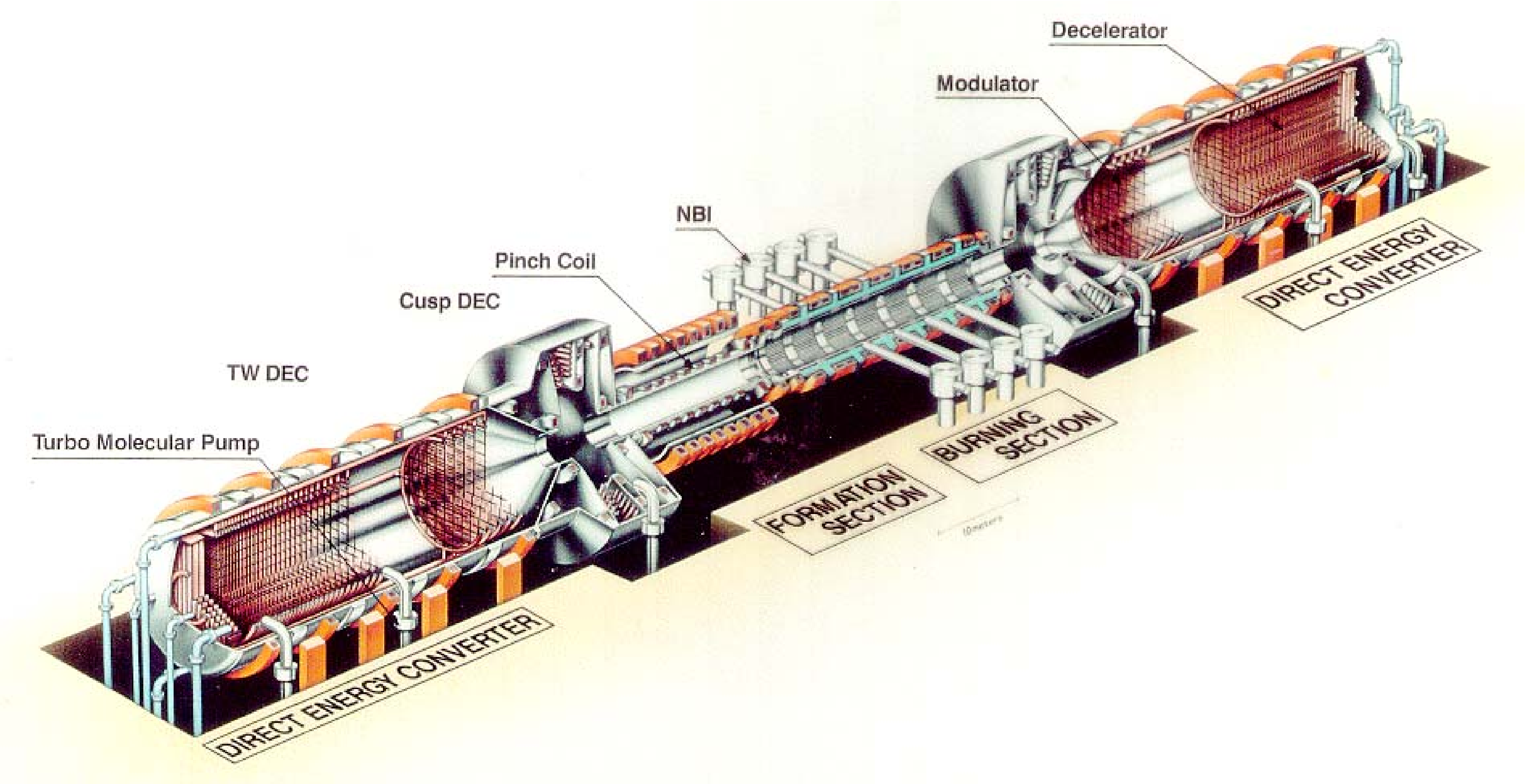
- Very high $\beta \equiv P_{plasma}/P_{B\text{-field}}$
- Linear external B field
- Cylindrical geometry
- Requires efficient current drive



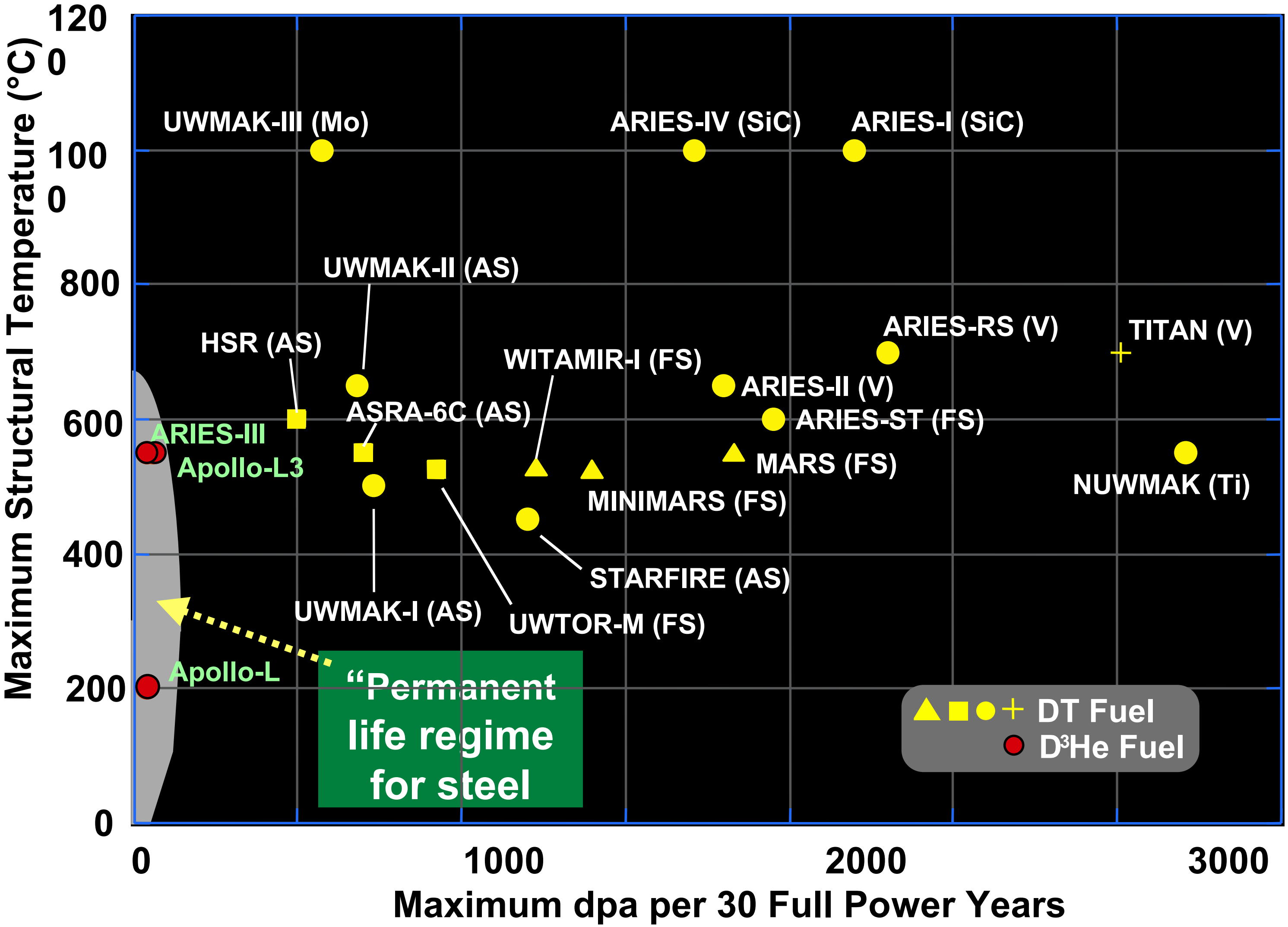
FRC as Power Source and Ion Engine for High Energy Space Missions

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

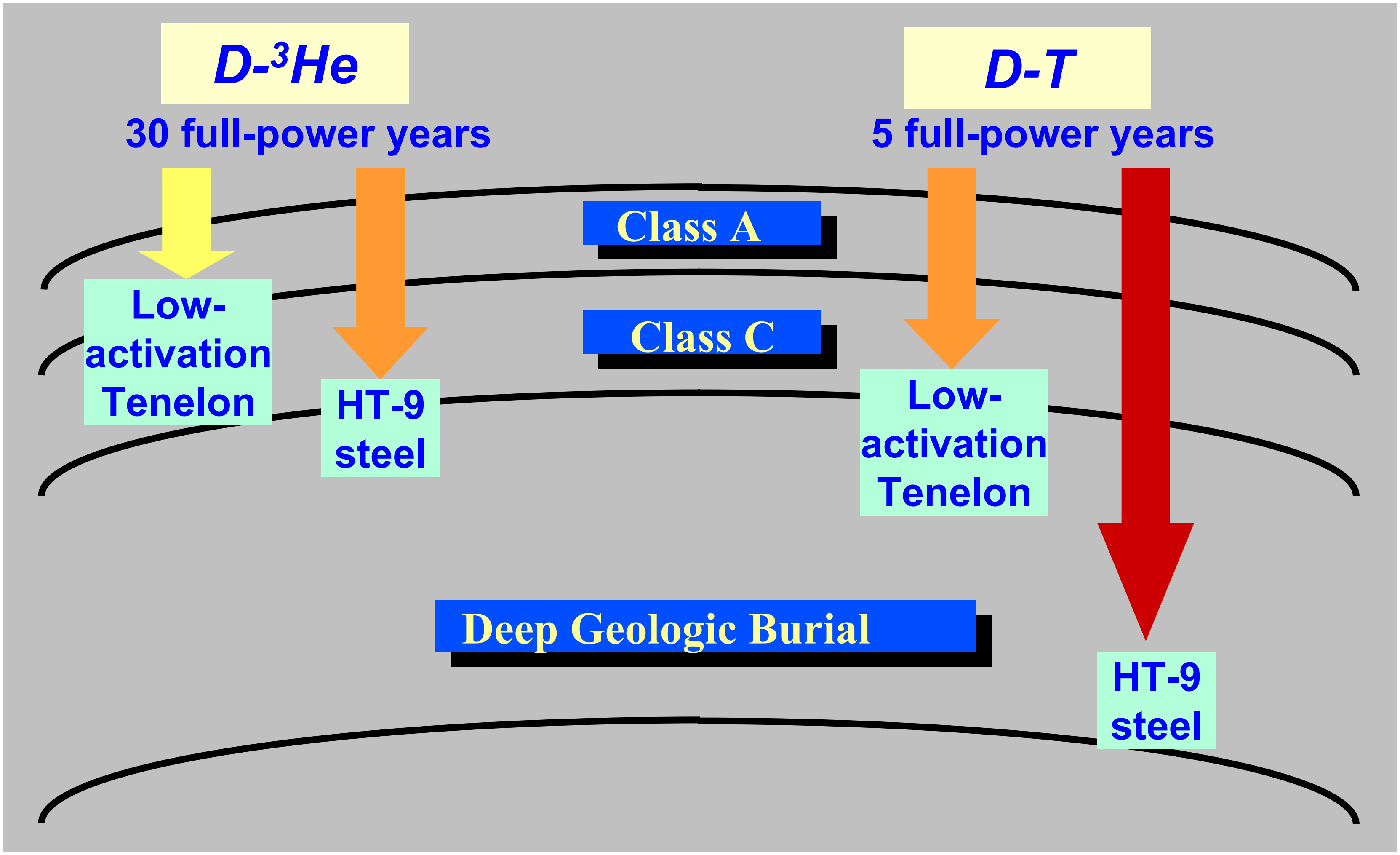
ARTEMIS Field-Reversed Configuration (D-3He, Momota, et al., NIFS, 1992)



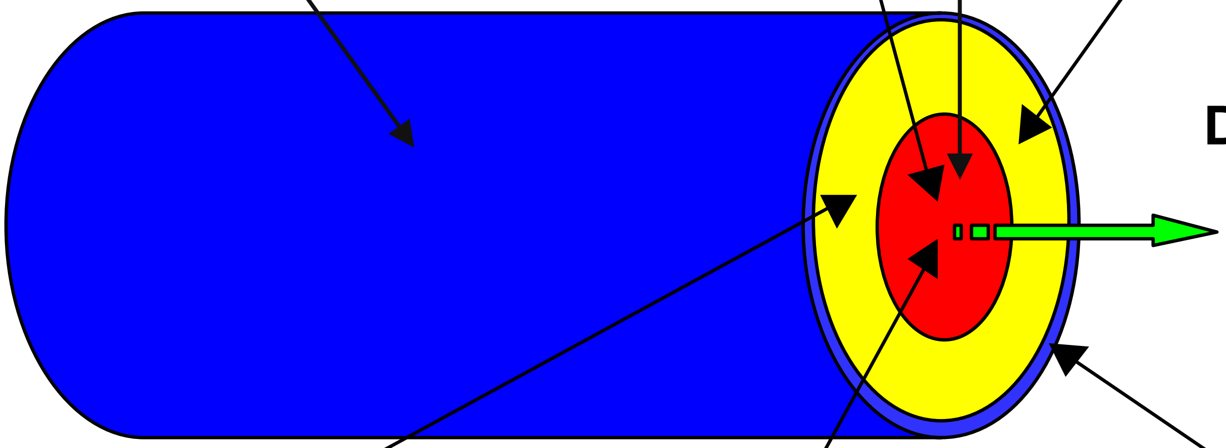
The Low Radiation Damage in D-^{3}He Reactors Allows Permanent First Walls and Shields to be Designed



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

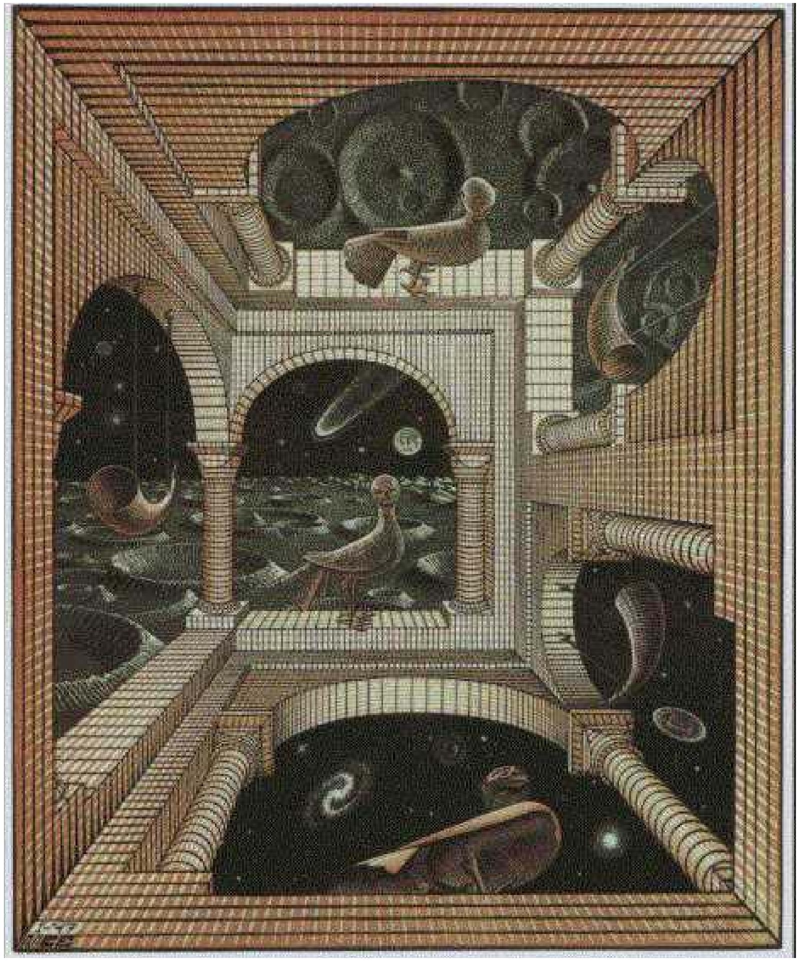
Direct converter for increased electric power per unit fusion power

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

Small plasma to reduce space for D-T shielding

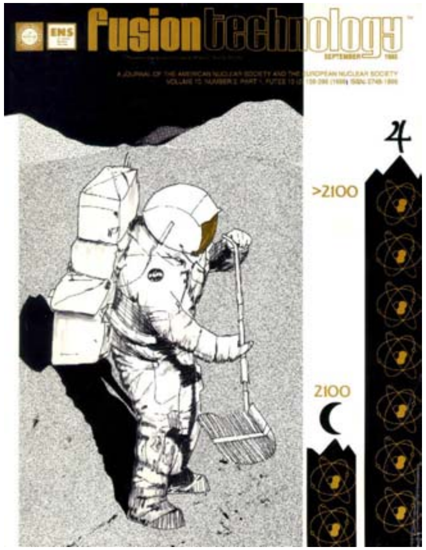
Superconducting, high-field magnet for high fusion power density

The ^{3}He Fuel Source is an Issue —So Think Outside the Box

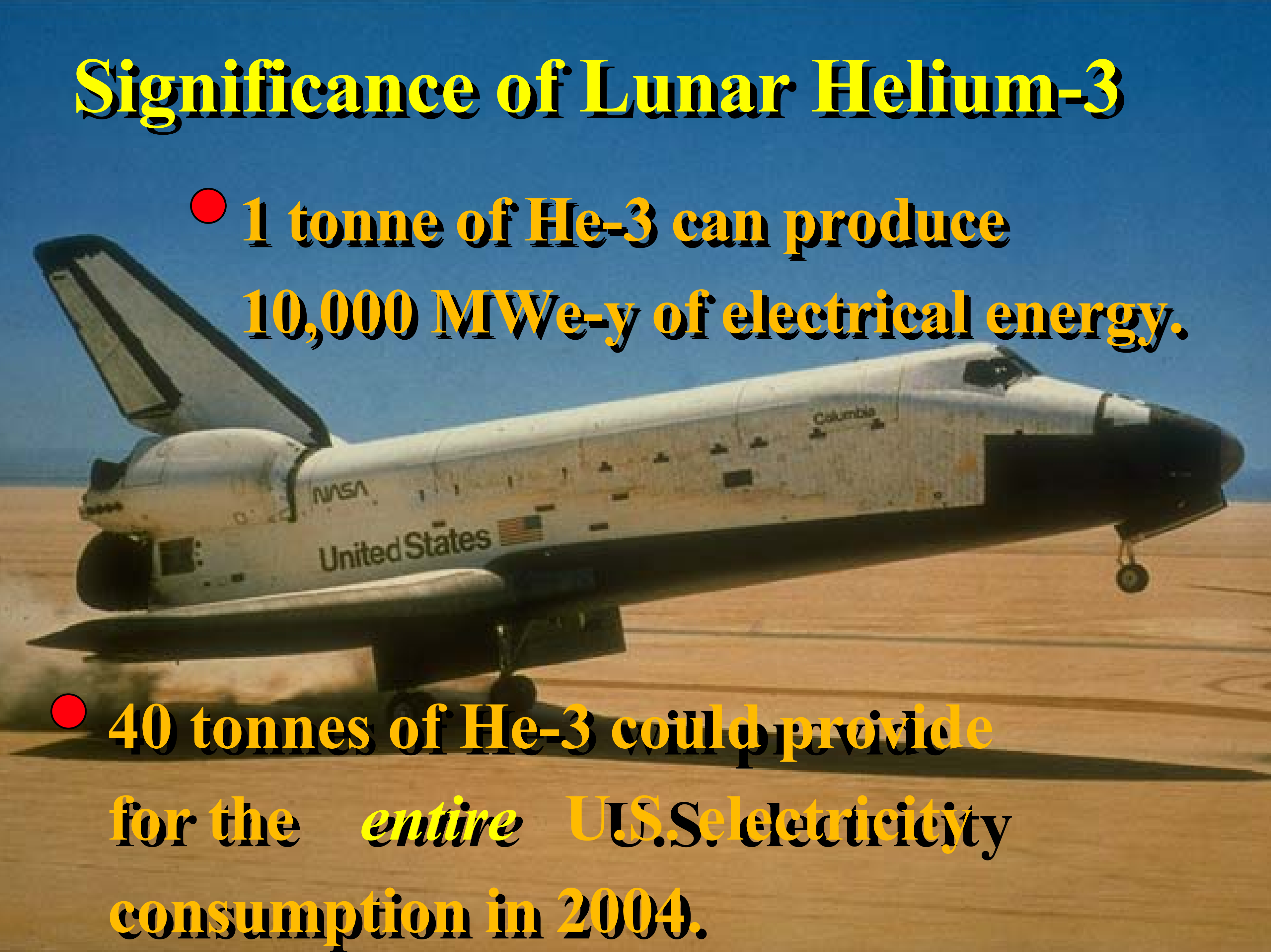


Escher, Other World, 1947

- ~400 kg ^{3}He accessible on Earth (~8 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
- L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technology* **10**, 167 (1986).

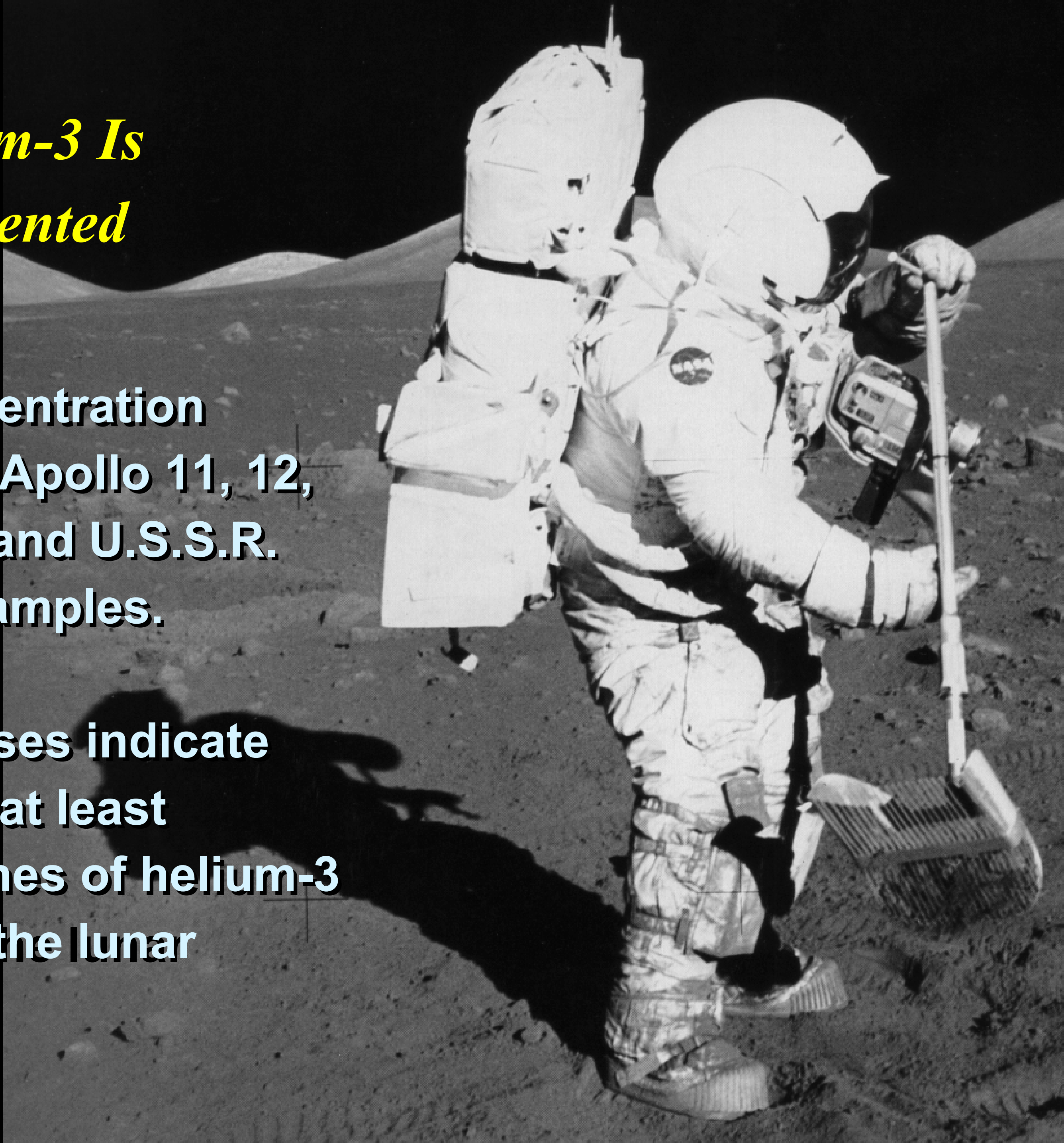


Significance of Lunar Helium-3



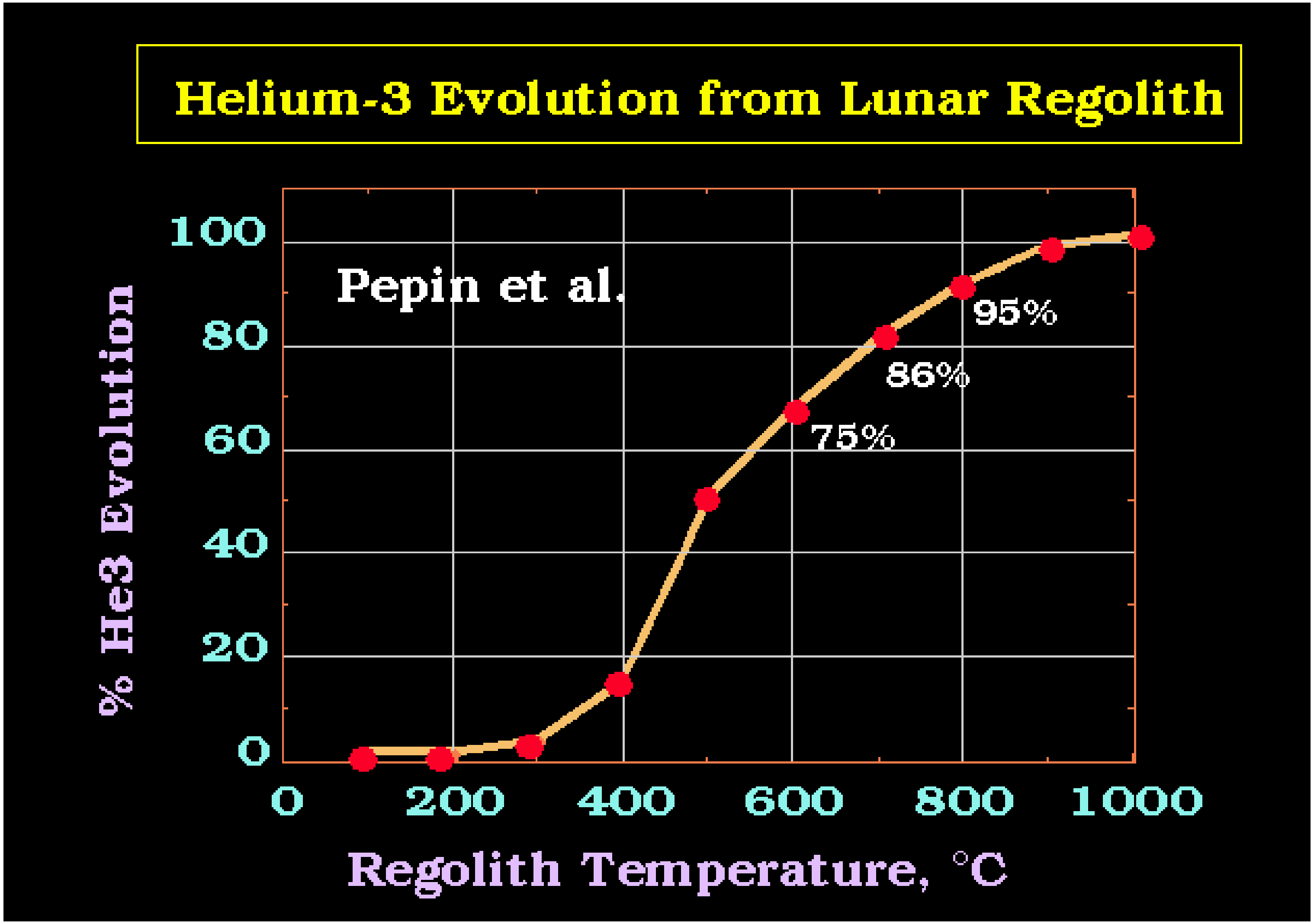
- 1 tonne of He-3 can produce 10,000 MWe-y of electrical energy.
- 40 tonnes of He-3 could provide for the *entire* U.S. electricity consumption in 2004.

Lunar Helium-3 Is Well Documented



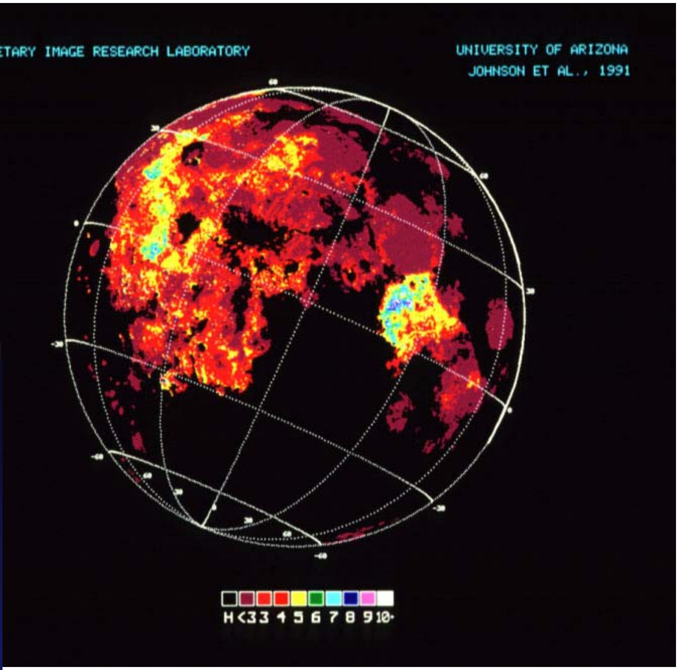
- Helium-3 concentration verified from Apollo 11, 12, 14, 15, 16, 17 and U.S.S.R. Luna 16, 20 samples.
- Current analyses indicate that there are at least 1,000,000 tonnes of helium-3 embedded in the lunar surface.

^{3}He Evolution from Lunar Regolith

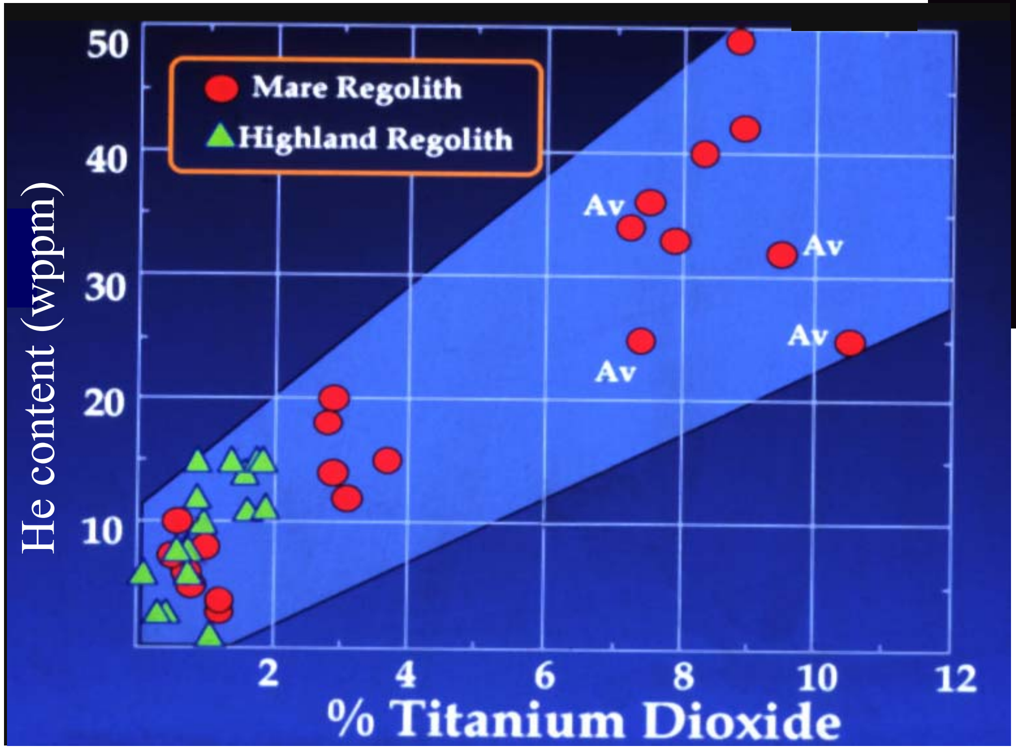


He Content Correlates Well with Ti Content

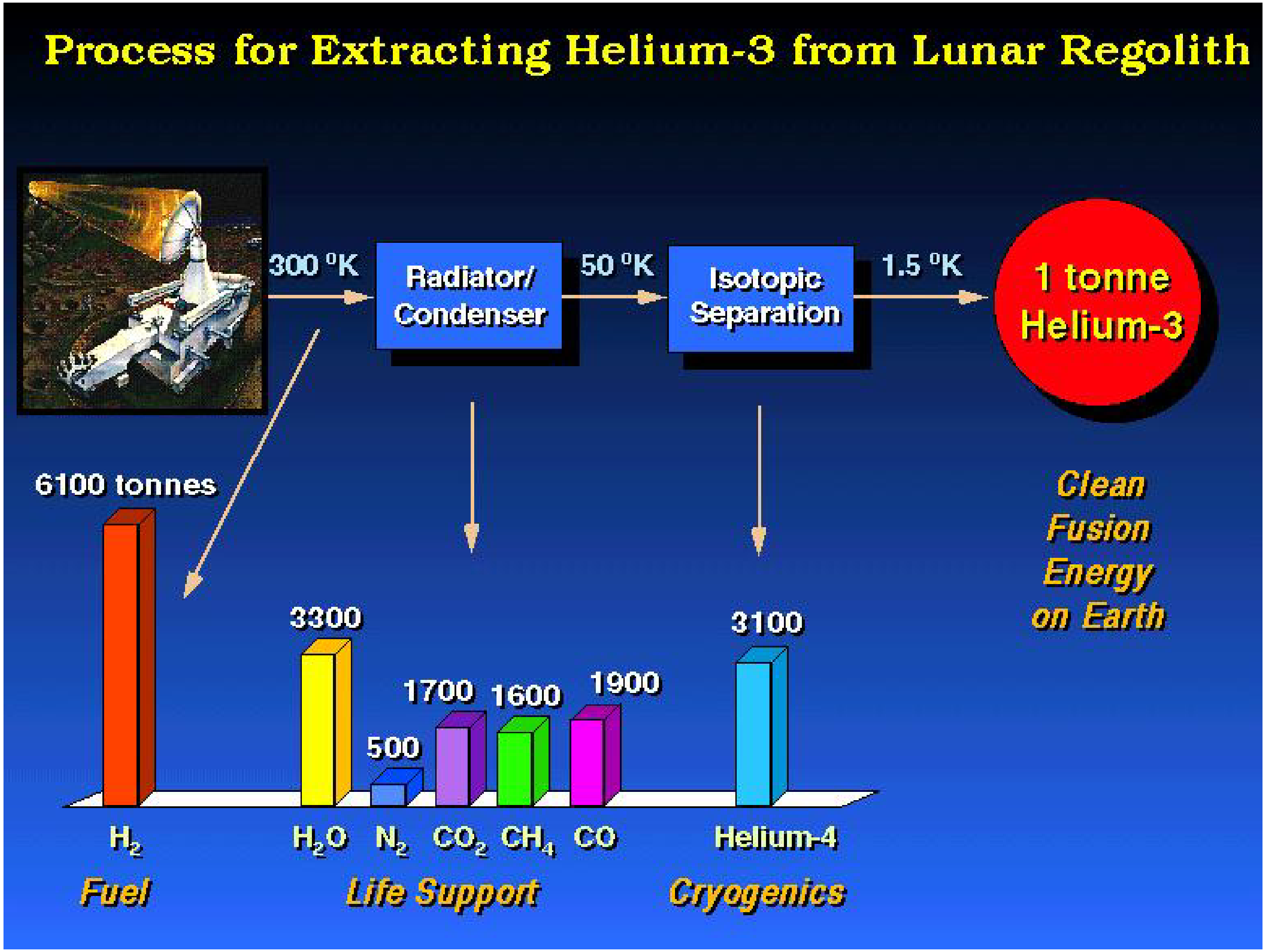
Spectral reflectance map
of lunar Ti content



Measured correlation
of He and Ti contents

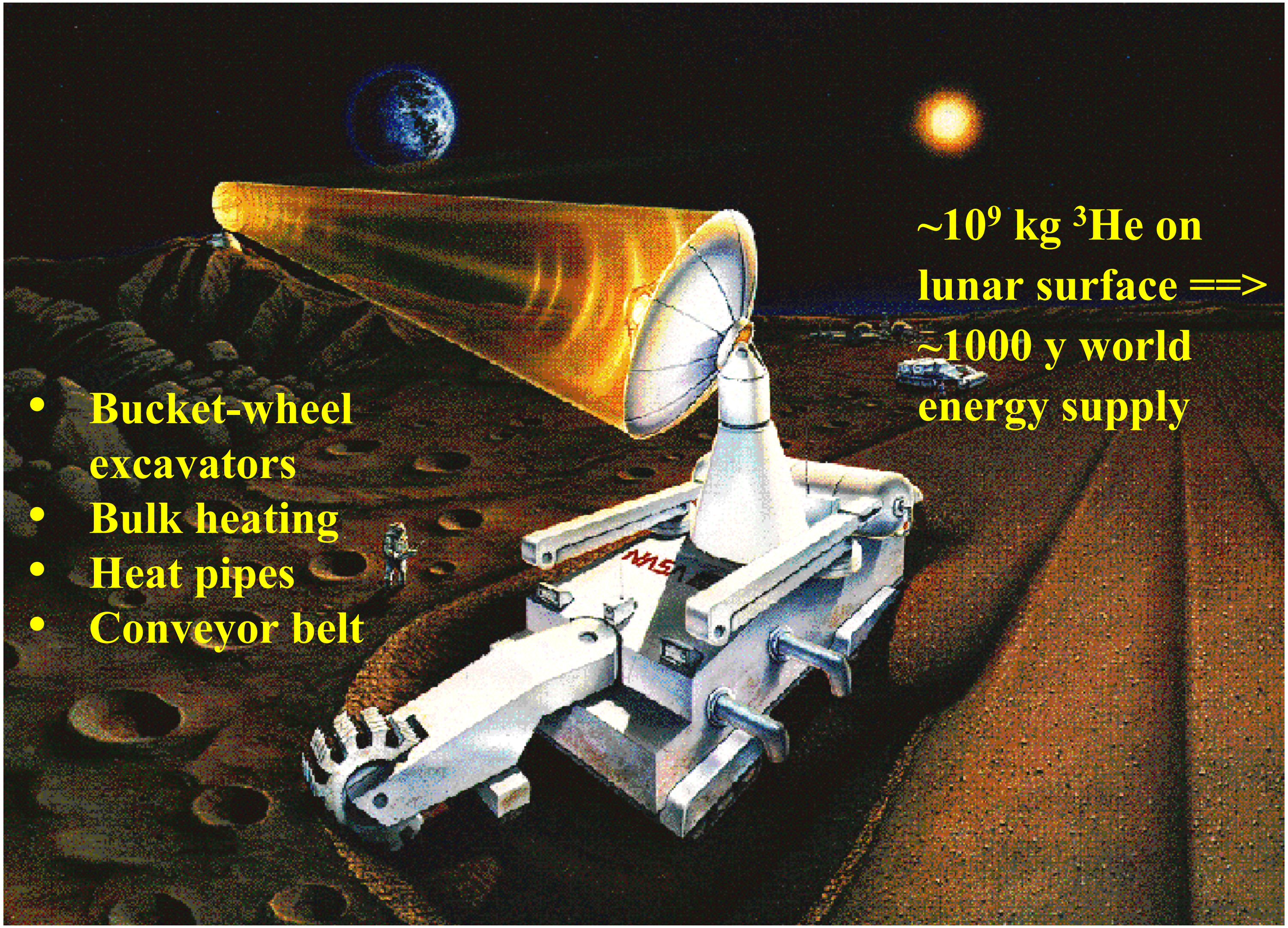


Lunar ^{3}He Mining Produces Other Volatiles Useful for Sustaining a Lunar Base



Process for Extracting Helium-3 from Lunar Regolith

Lunar ^{3}He Mining Would Use Well-Developed Terrestrial Technology



- Bucket-wheel excavators
- Bulk heating
- Heat pipes
- Conveyor belt

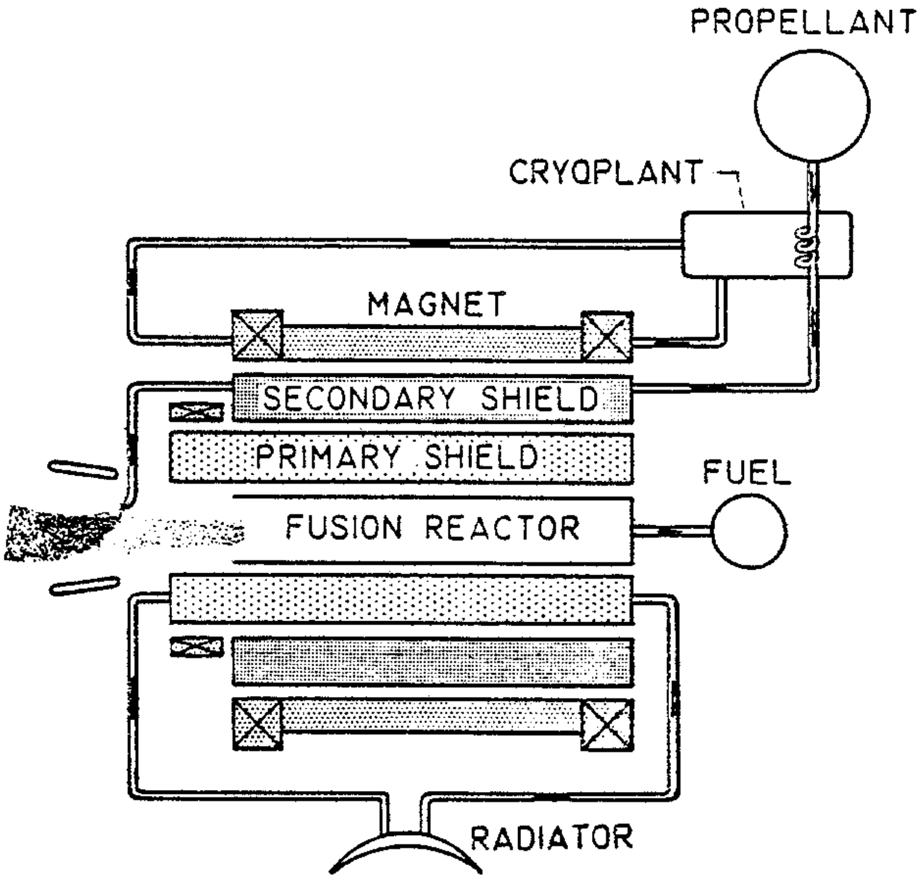
~10^{9} kg ^{3}He on lunar surface ==> ~1000 y world energy supply

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

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

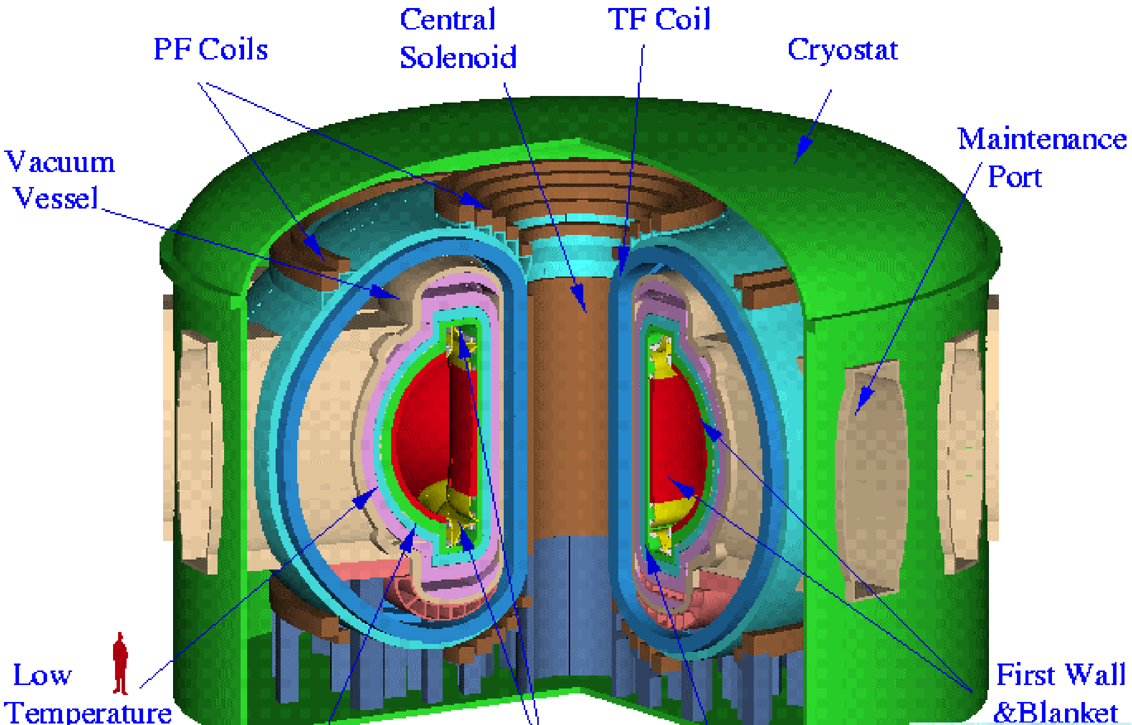
"If controlled thermonuclear fusion can be used to power spacecraft for interplanetary flight it will give important advantages over chemical or nuclear fission rockets.

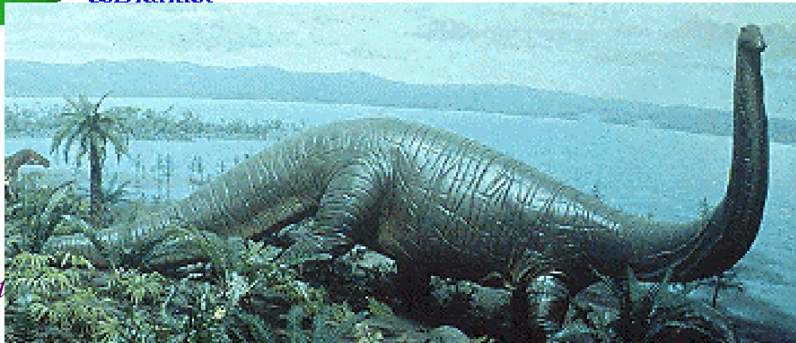
The application of superconducting magnets and a mixture of deuterium and helium-3 as fuel appears to be the most promising arrangement."



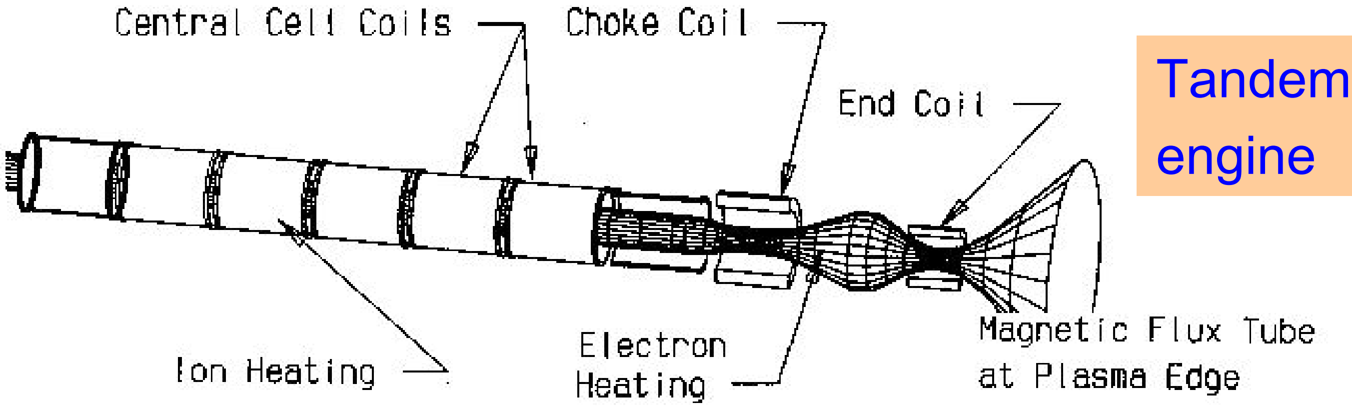
Conventional Tokamaks Have High Mass

Cutaway of the ARIES-RS Power Core





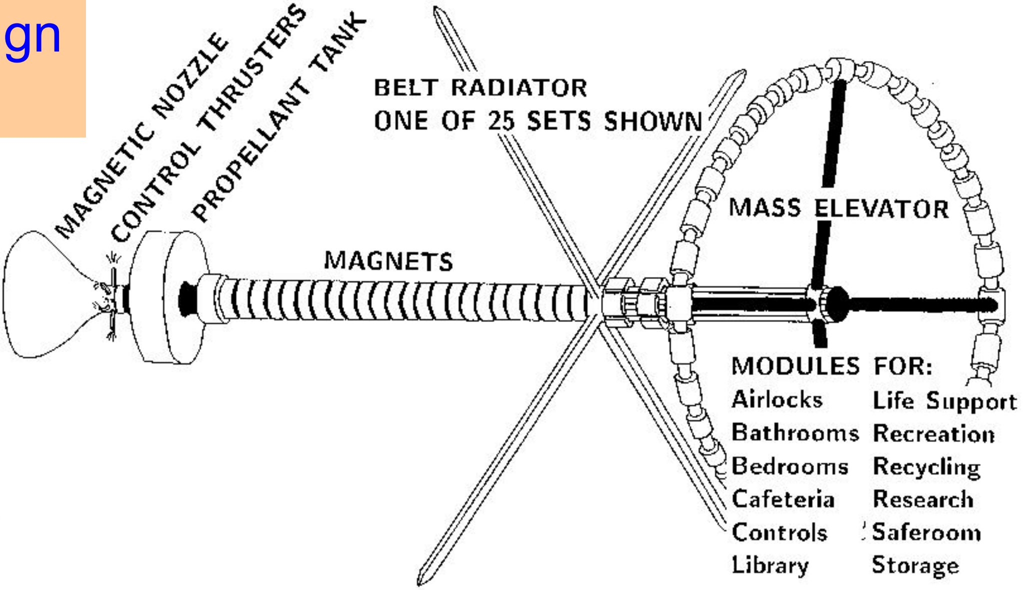
D-^{3}He Space-Propulsion Tandem Mirror



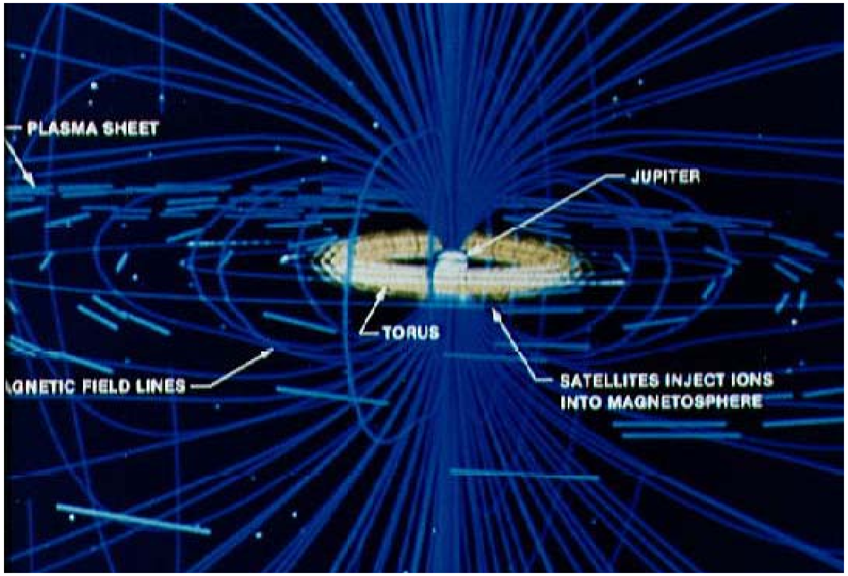
Tandem mirror engine

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

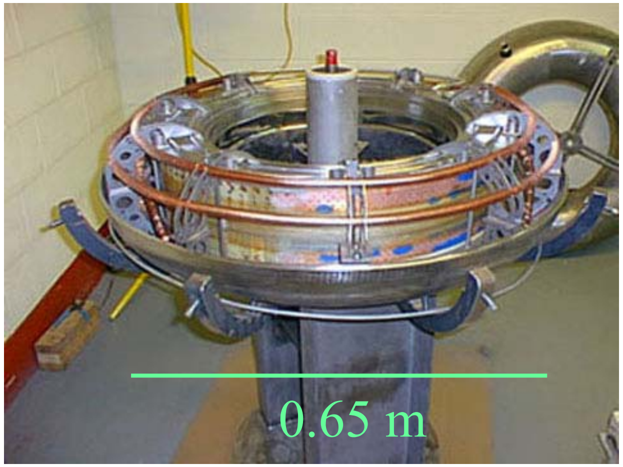


The Dipole Configuration Offers a Relatively Simple Design That an MIT/Columbia Team Is Testing

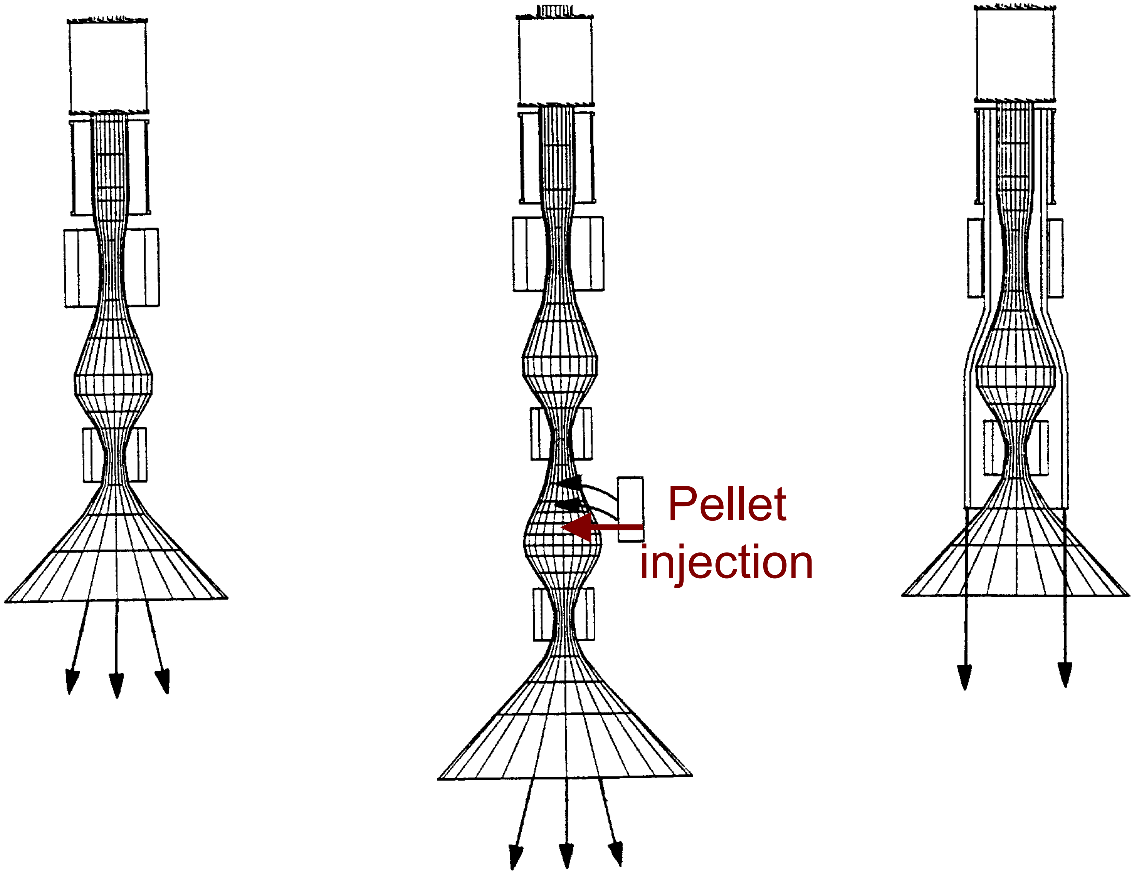


Io plasma torus around Jupiter

LDX experiment
(MIT)



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



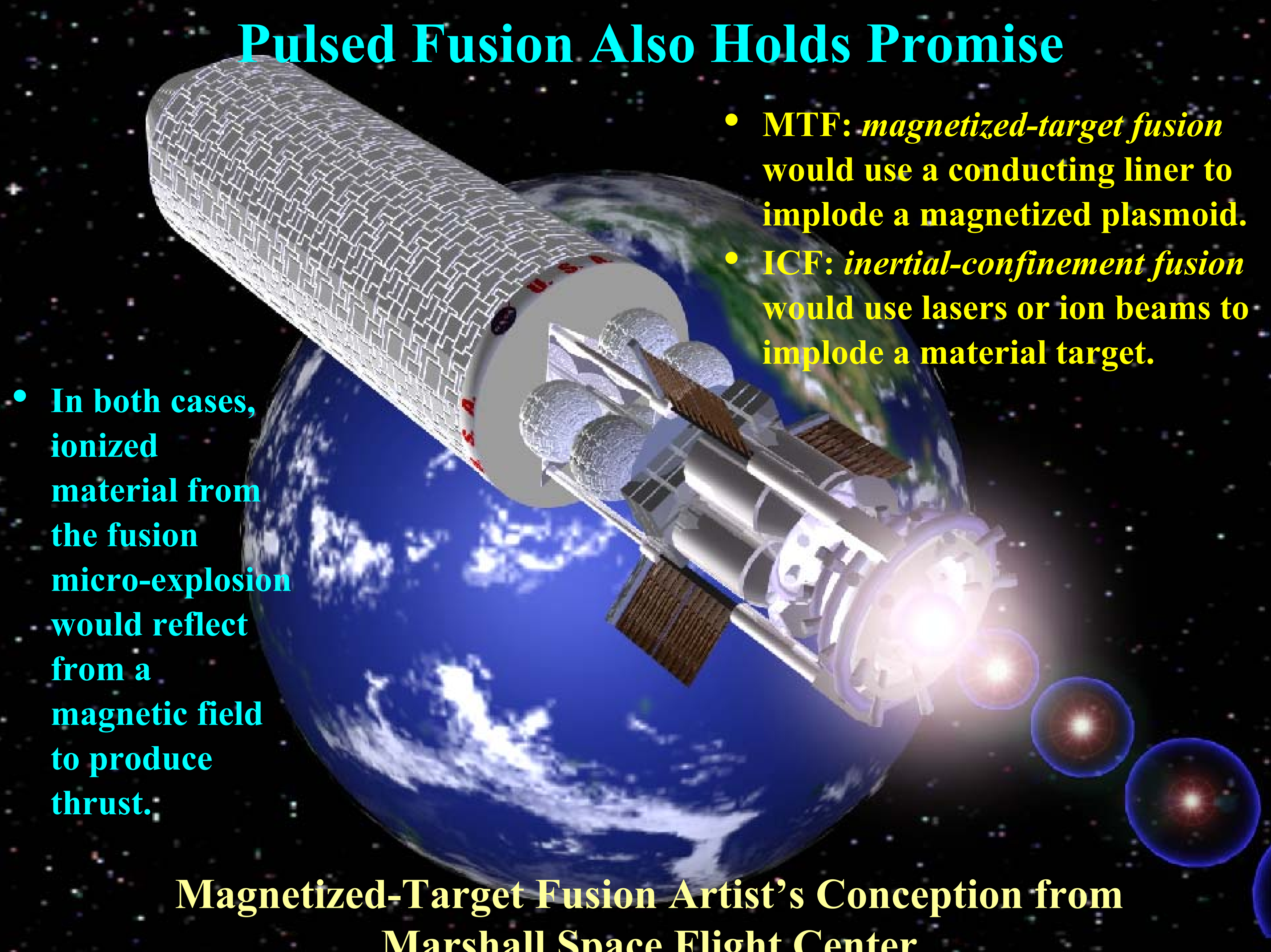
Fuel plasma exhaust

Mass-augmented exhaust

Thermal exhaust

Pellet injection

Pulsed Fusion Also Holds Promise

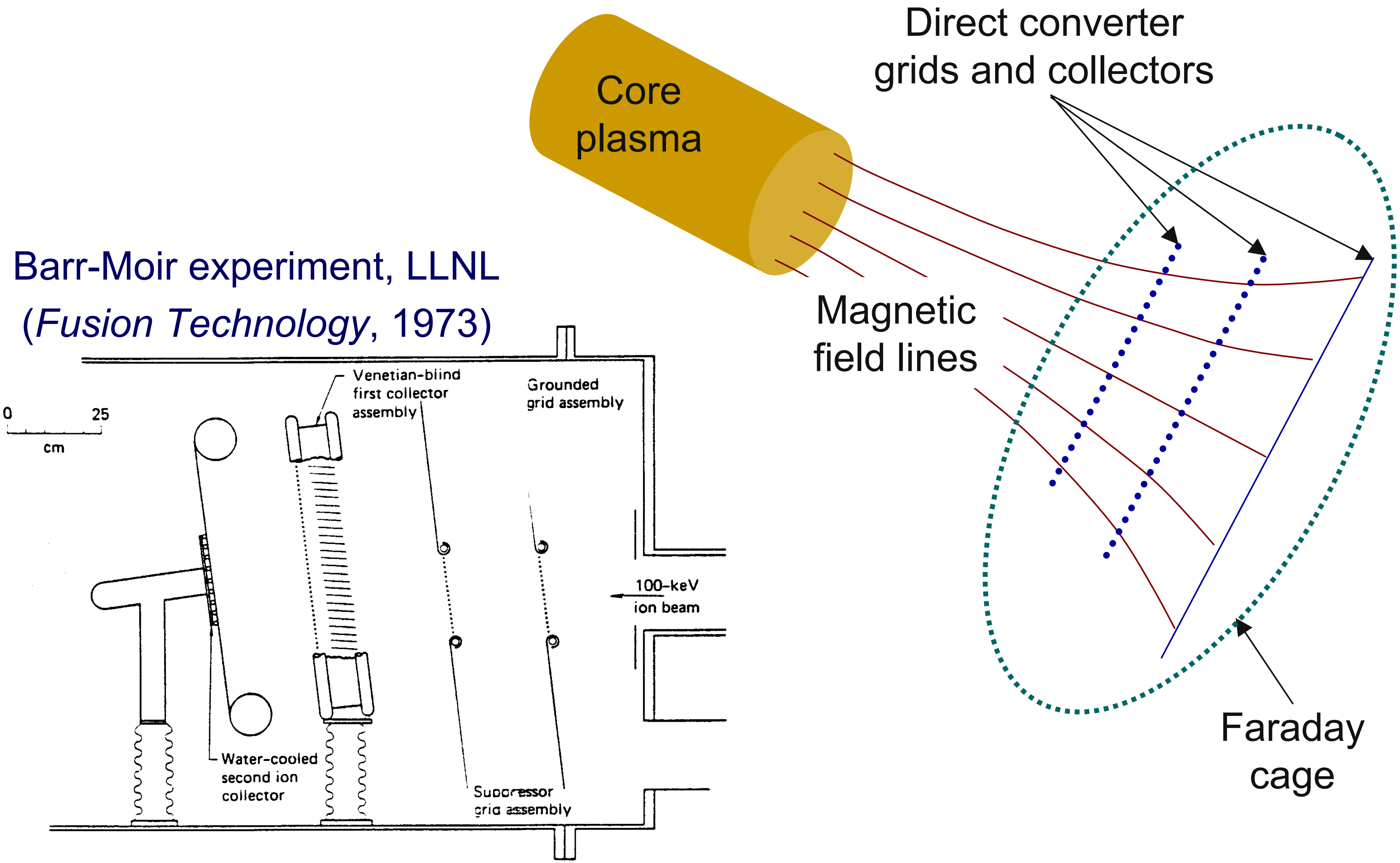


- MTF: *magnetized-target fusion* would use a conducting liner to implode a magnetized plasmoid.
- ICF: *inertial-confinement fusion* would use lasers or ion beams to implode a material target.

- In both cases, ionized material from the fusion micro-explosion would reflect from a magnetic field to produce thrust.

Magnetized-Target Fusion Artist's Conception from Marshall Space Flight Center

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



Core plasma

Direct converter grids and collectors

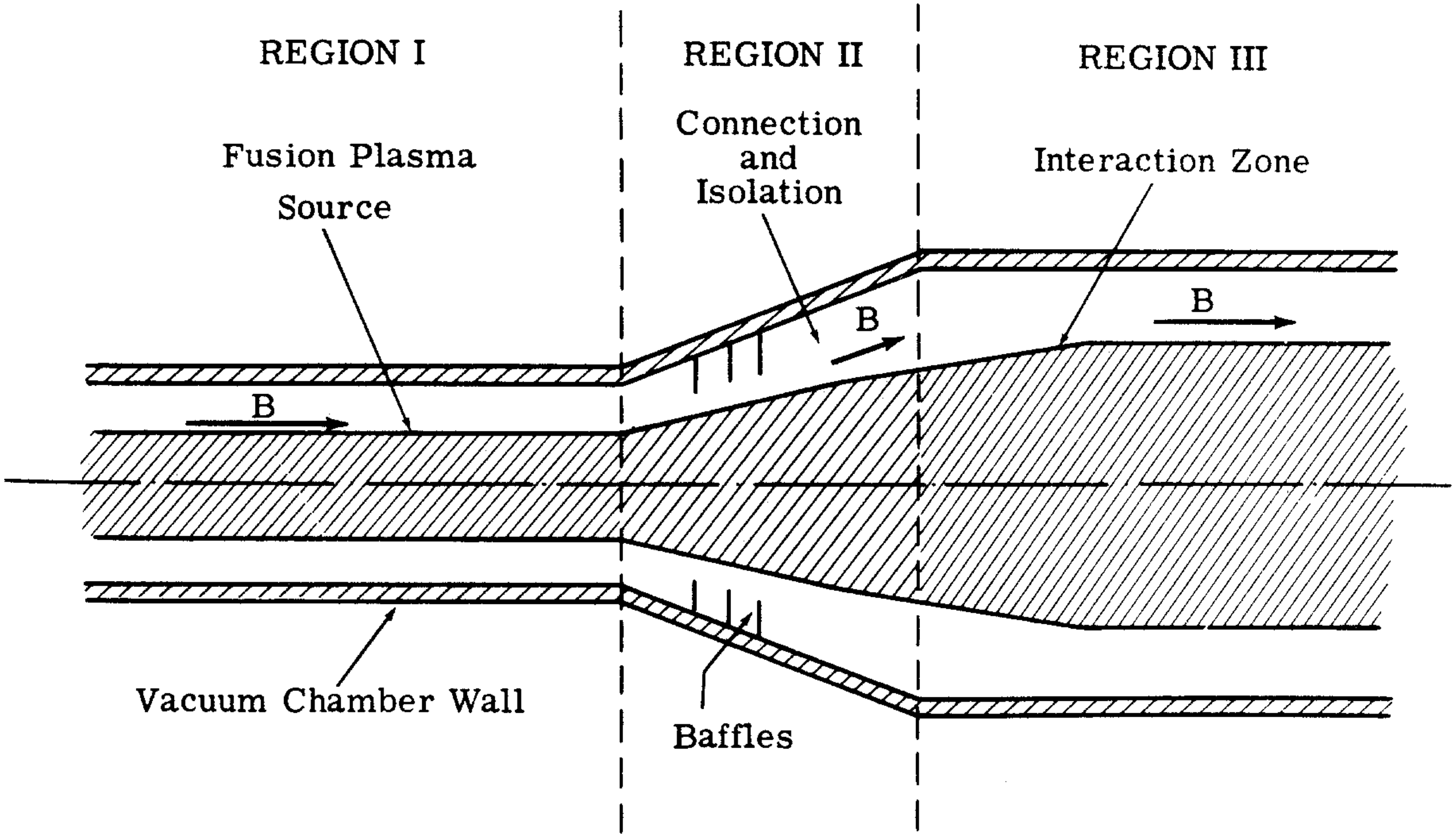
Magnetic field lines

Faraday cage

Barr-Moir experiment, LLNL

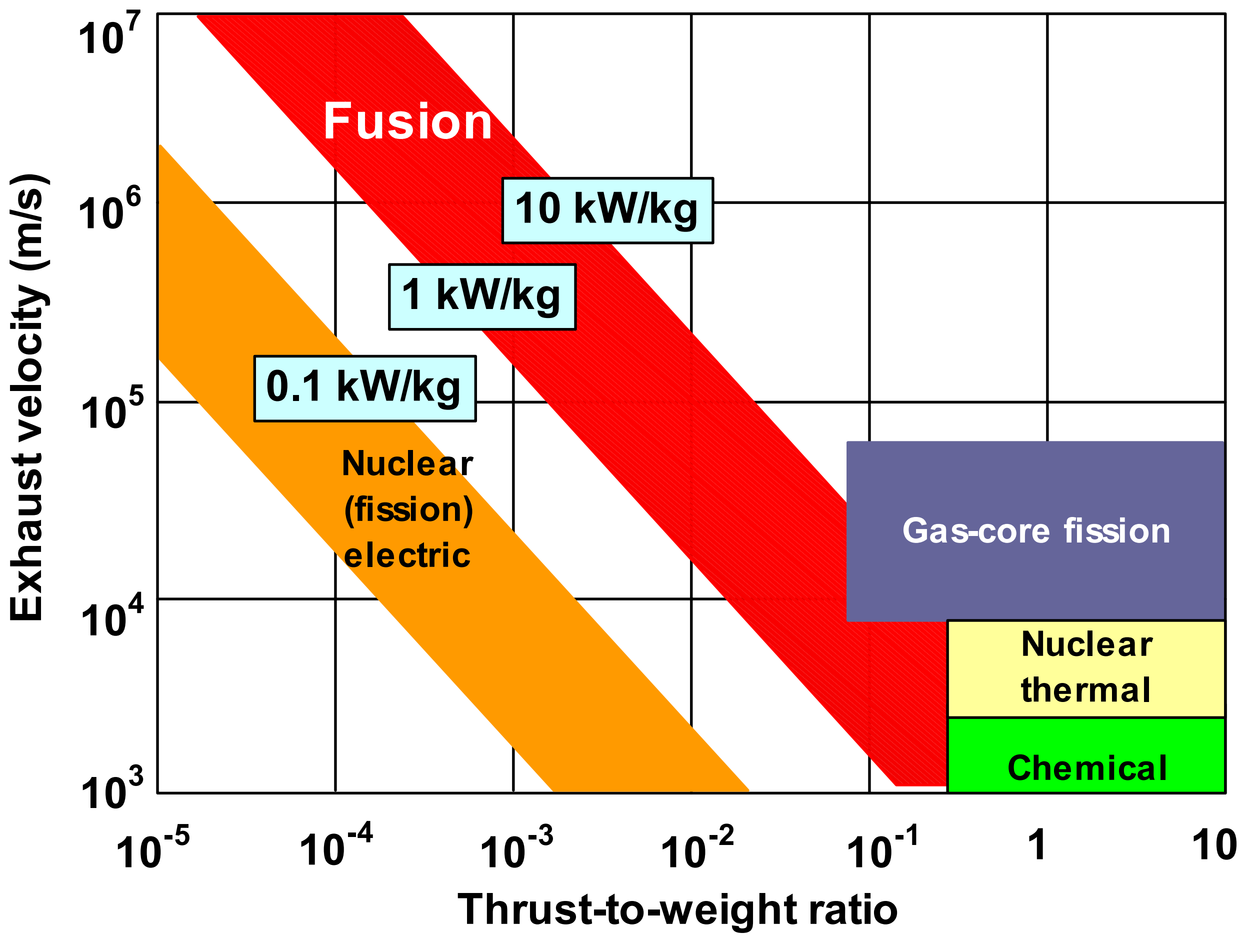
(*Fusion Technology*, 1973)

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).

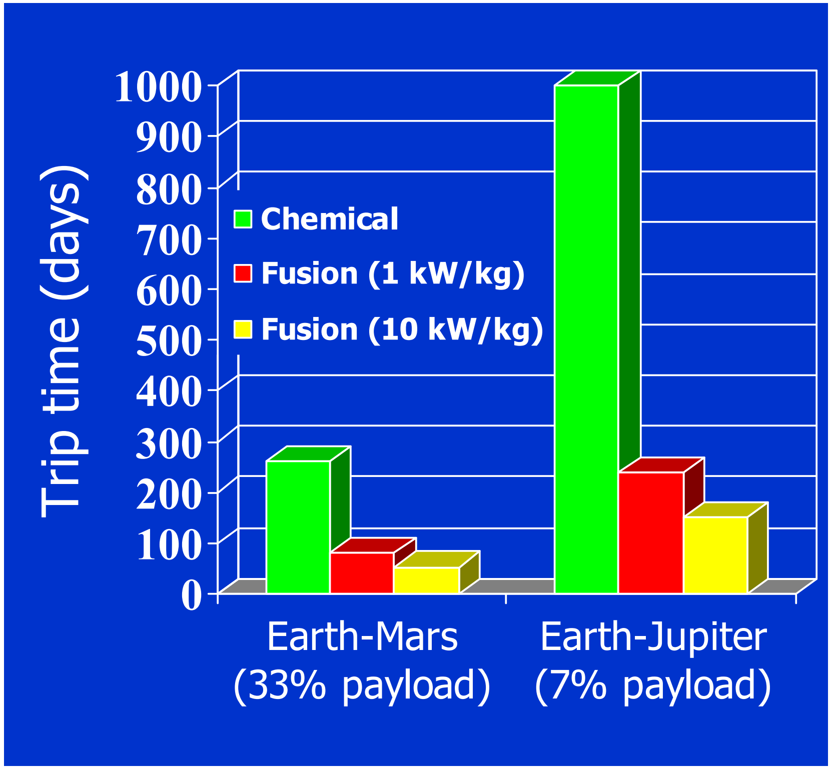
D-^{3}He Fusion Will Provide Capabilities Not Available from Other Propulsion Options



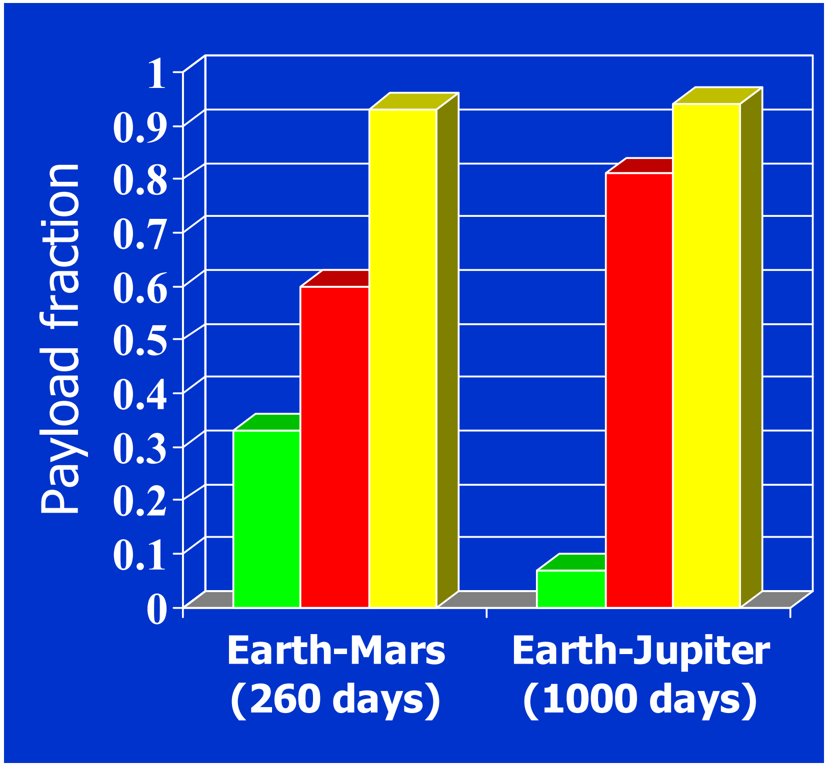
Fusion Propulsion Would Enable Attractive Solar-System Travel

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

Fast human transport



Efficient cargo transport



Final Thought:

Where Do We Go from Here?