Imagine --
Terrestrial Fusion Power Abounds
Humans Ready to Explore Saturn to Find Life

1. Fusion, the only known energy catapult for deep-space travel
2. Needs direct propulsion from D-^{3}He fusion energy
3. How about Coaxial Helicity Ejection from bootstrap overdriven ST?

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Other Applications, Energy WG
1999 Fusion Summer Study
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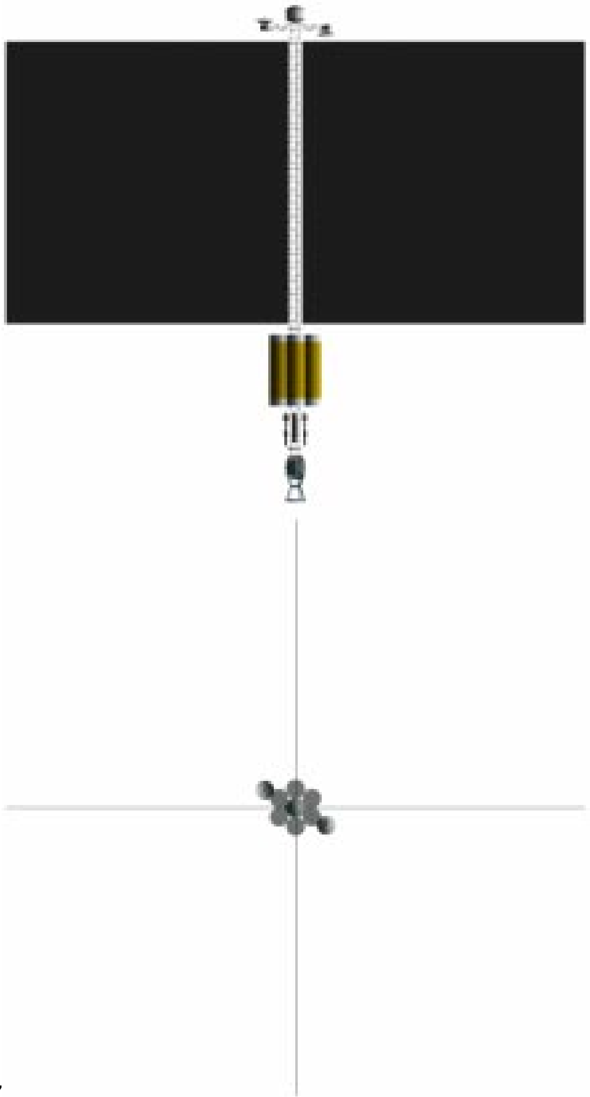
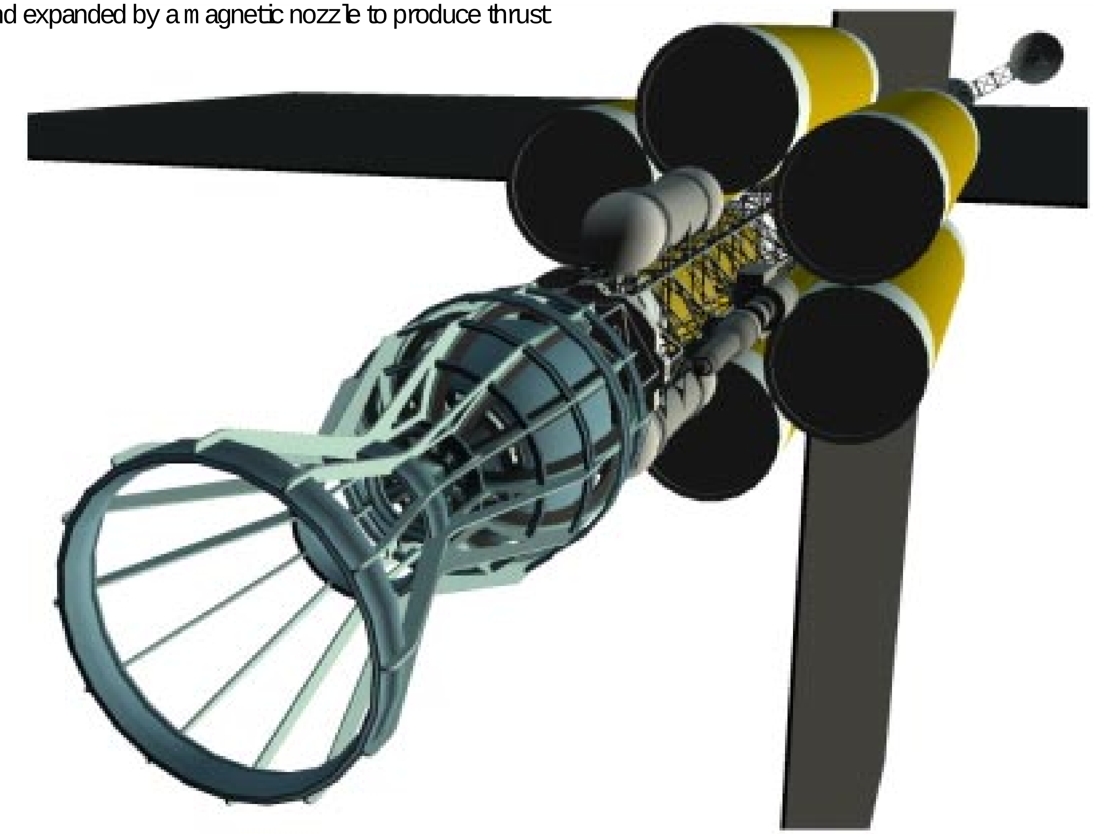
Nuclear Fusion Propulsion Vehicle for Fast Outer Solar System Transportation

Direct thrust nuclear fusion propulsion using magnetic nozzle:
a propulsion system utilizing D^3He to fuel a fusion reactor,
producing plasma to directly heat thrust augmenting hydrogen propellant,
which is confined and expanded by a magnetic nozzle to produce thrust





Vehicle Characteristics

- Spherical torus nuclear fusion reactor plasma source (8,000 MW total fusion power; D^3He fueled)
- Single 5,000 to 7,000 lb_f thrust magnetic nozzle engine
- Specific impulse: 20,000 to 50,000 sec (total vehicle alpha = 4 kW/kg)
- Dual, counter rotating turboshaft, gaseous Helium Brayton power cycle producing 400 MWe
- Power supports plasma current drive through neutral beam injection, also RCS and refrigeration
- Continuous thrust acceleration/deceleration radial interplanetary transfers
- 8 month one way Earth to Saturn trip time (8.5 AU; w/planetary refueling)
- Zero-g habitat for crew of 6

ST Propulsion, 1999 Fusiion Summer Study

Rationale for Selection of Spherical Torus

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- Closed, magnetic confinement configuration (as opposed to open or inertial)
  - high power density achievable
  - improved confinement
  - density, temperature profile peaking
- Small aspect ratio spherical torus
  - large tokamaks dominate research effort, funding, but mass and size unappealing for space propulsion applications
  - compact toroids (spheromaks, etc.), field reversed, etc. very attractive for propulsion, but largely conceptual, limited reactor databases make engineering system assessments difficult

  - Small aspect ratio spherical torus selected
  - compromise between tokamaks and more compact toroids
  - extrapolatable databases and reactor mass properties, operations, performance
  - similar attractive features of more compact toroids

Bootstrap Current Overdrive

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- Greater confinement, fusion product, required of D3He fusion --- greater magnetic fields, favoring higher beta, implies greater plasma current
- Diffusion driven, bootstrap current can be greater than required --- "overdrive"
- Bootstrap current overdrive mitigates large, external current drive
- Resultant plasma profile usually does not match desired equilibrium --- external tailoring of profile required
- Bootstrap current overdrive expected to facilitate plasma current control through fueling rate
- With CHE, bootstrap current overdrive can adjust energy of exhausted plasma, facilitating propulsion operation while maintaining plasma control
- Assumed F_{bs} = 1.16 requiring 108 MW external heating

Coaxial Helicity Ejection

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- Magnetic helicity approx product of toroidal and poloidal magnetic fluxes
- Helicity can be injected by supplying current through divertor while maintaining difference of potential across divertor plates (power input)
- Inverse process, Coaxial Helicity Ejection, expected to occur upon shutdown, potential mechanism to control exhausting power for propulsion
- CHE to work in concert with bootstrap current overdrive to maintain reactor steady state operation
- Series of experiments planned at DOE PPPL's NSTX
  - establish CHE theory
  - assess feasibility of CHE to enable propulsion
  - perform proof of concept experiments in conjunction with already planned DOE campaign

Magnetic Nozzle

- Used to directly convert charged transport power into thrust
  - mixes high enthalpy reactor plasma with slush hydrogen thrust augmentation propellant
  - accelerate propellant plasma through diverging magnetic field lines
- Largely skeletal design
  - 3 TF coil-like magnets (smaller current, smaller field)
  - lightweight Al Gr/Ep composite structure
  - reservoir coil: small diameter (~2 m radius structural, 10 cm magnetic)
  - throat coil: same as reservoir coil
  - exit coil: larger (arbitrary)
  - central propellant injector aligned w/reactor central bore
- Assumed 80% efficiency based on lower power EP experience
- Current magnetic nozzle experimental campaign of NASA LeRC/OSU/LANL
  - detachment problem
  - nozzle design, fab, test (He, H_2)
  - thrust augmentation propellant injection (H_2)

Necessity for Coaxial Helicity Ejection Experiment

- Effective propulsion system requires removal of large quantities (1,000's MW) of charged transport power from reactor scrape-off layer for transfer to propulsion system (magnetic nozzle)
- Power extraction method must have minimum adverse impact on ignited, steady state reactor operation and will be very reactor concept dependent
- Current research reactor divertors serve many fundamentally different purposes
- Coaxial Helicity Ejection (CHE) appears to be a leading candidate method for power extraction through the divertor to enable practical direct fusion propulsion