Systems-Level Modeling of a Beam-Core Matter-Antimatter Annihilation Propulsion System

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Continuing interest in assessing the feasibility of performing interstellar missions has prompted renewed interest in the "beam-core" matter-antimatter annihilation propulsion concept. In this engine, equal amounts of matter (protons) and antimatter (antiprotons) are combined; during the annihilation reaction, about 62% of the initial rest mass is converted into the mass-energy of high-speed (0.94c) charged pions ($\pi^{\pm}$). When deflected and focused by a magnetic nozzle, the charged pion "beam" has an effective specific impulse (I_{sp}) of about 10^7 lb_f-s/lb_m. This I_{sp}, corresponding to an effective exhaust velocity of 0.33c, makes the beam-core engine an attractive candidate for interstellar missions requiring high velocities (i.e., $\Delta V >$ 0.1c). The purpose of this paper is to identify, evaluate, and determine the systems-level performance parameters (e.g., mass, power, efficiency, etc.) of the various subsystems associated with a complete beam-core matter-antimatter annihilation propulsion system that could be used for an interstellar mission.

Previously, John Callas (JPL) had used a Monte-Carlo simulation method to model particle ($\pi^{\pm}$) trajectories in a beam-core engine with a single-loop magnetic nozzle, such as that illustrated in Figure 1. This yielded the previously mentioned result of an effective I_{sp} of 10^7 lb_f-s/lb_m. Chris Paine (Brown University) had also demonstrated the feasibility of non-contact storage of solid anti-molecular hydrogen (anti-SH_2) by using a sombrero-shaped magnetic field (see Figure 2) to levitate small droplets of liquid and solid hydrogen (LH_2, SH_2) as a normal-matter simulant for anti-SH_2. Paine also demonstrated that the magnetic field from a current-loop in a wire could be used to push the solid or liquid H_2 pellets around the ring-shaped levitating field. The two remaining primary feasibility issues involve the demonstration of a low-cost, high-capacity technique for the production of antiprotons, and the "non-contact" conversion of a low-density antiproton plasma to anti-atoms, then to anti-molecules, and then the cooling of the anti-molecules to form "ice" crystals of anti-SH_2.

These latter two issues are decidedly non-trivial; they may represent intrinsic "show-stoppers" that can not be resolved, although work is continuing in this area. However, for the purposes of this paper we assume that the technical issues of producing, storing, and using large amounts of antimatter in a rocket propulsion system have been solved. We will then focus on identifying and evaluating the various subsystems required to implement such a propulsion system, with a particular emphasis on deriving scaling equations (e.g., mass = f(power)) that can be used in mission analyses to assess the mission benefits (e.g., initial vehicle wet mass, trip time, payload mass, etc.) of such a system.

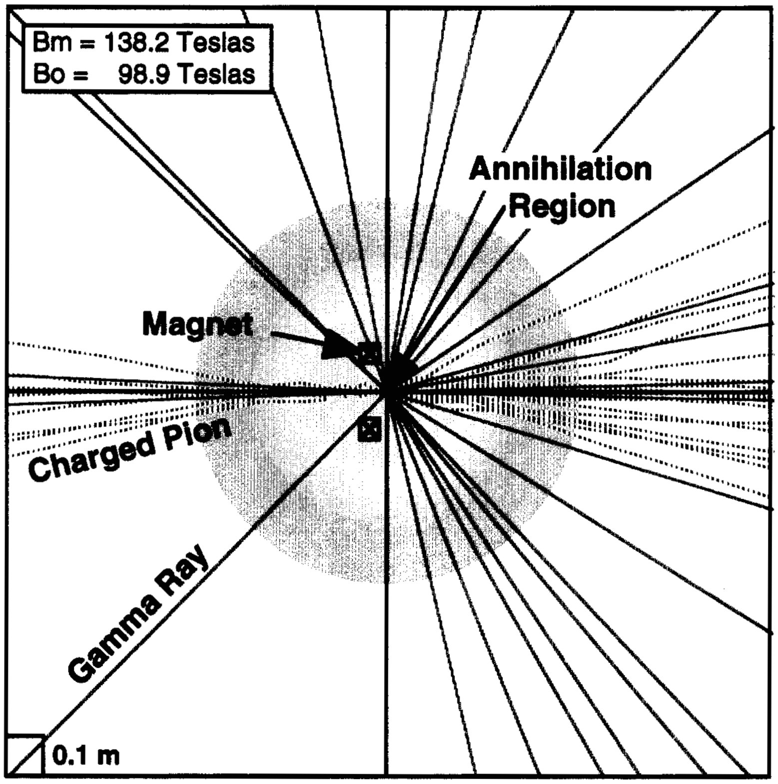

Figure 1. Monte-Carlo Simulation of a Beam-Core Matter-Antimatter Annihilation Rocket Engine.
(Curved dashed lines are charged pions; straight solid lines are gamma rays)

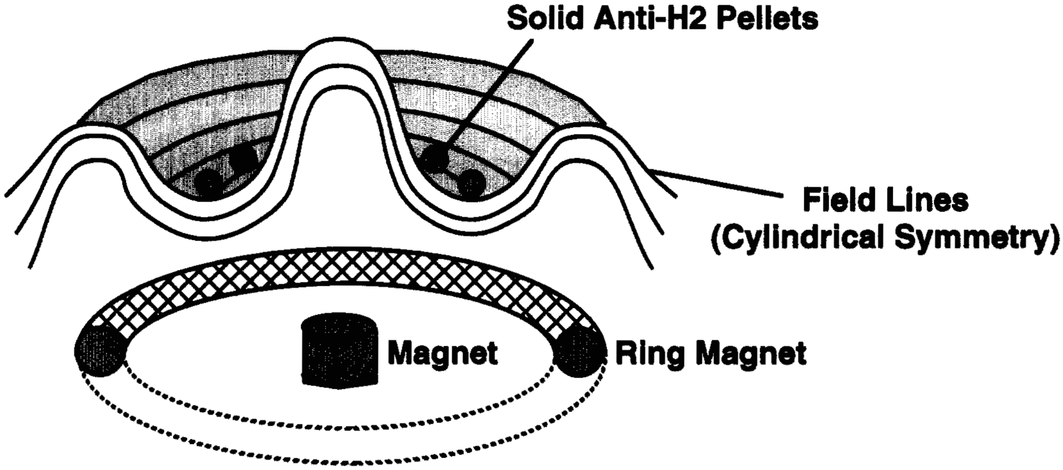

Figure 2. Magnetic Levitation of Solid or Liquid Hydrogen Droplets in a Sombrero-Shaped Magnetic Field.

Figure 3 illustrates an example of the major systems comprising a conceptual beam-core engine propulsion system. For example, the engine consists of a ring-shaped magnet which generates the field of the magnetic nozzle. The magnet requires a radiation shield for protection from the intense flux of gamma rays produced by the initial proton-antiproton and electron-positron annihilation process, and from the decay of the neutral pions produced in the proton-antiproton annihilation reaction. (The total energy content of these gamma rays correspond to 38% of the rest mass of the initial matter and antimatter reactants, or about 61% of the mass-energy content of the charged pion rocket engine exhaust.) Similarly, there is a larger shadow shield designed to protect the rest of the vehicle from the gamma ray radiation. The LH_2 and anti-SH_2 injector will also require shielding for any components that are directly exposed to radiation from the engine. The remainder of the various propulsion subsystems are located behind the vehicle shadow shield.

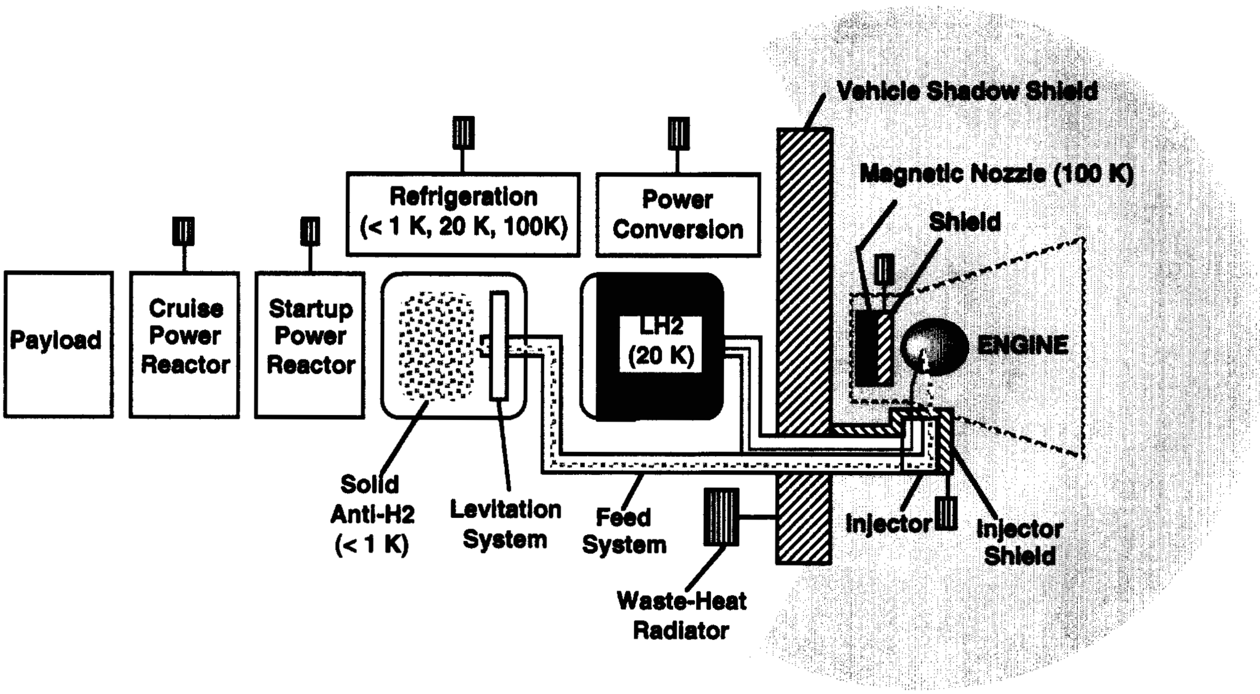

Figure 3. Major Systems of a Beam-Core Matter-Antimatter Annihilation Propulsion System

For example, a system is required to provide cruise power (when the engine is not running) for the refrigerators and anti-SH_2 levitation magnets. The refrigerators operate at a number of temperatures, ranging from ca. 100 K for superconducting magnets, to 20 K for LH_2 storage, and finally to < 1 K for anti-SH_2 storage. (Normally, SH_2 could be stored at its freezing point of 14 K; however, as Robert Forward has discussed previously, a much lower temperature is needed to prevent sublimation of the anti-SH_2, which is diamagnetic and therefore moves to a minimum in a magnetic field, because the gaseous anti-H_2, which is not diamagnetic and thus is not constrained by the magnetic storage field, would diffuse to the storage container walls and annihilate.) There is also an energy/power storage system to supply engine startup power and any shutdown/cooloff power needed. However, the primary power used to supply electricity to the various engine subsystems (e.g., magnets, injectors, feed systems, and additional refrigeration) during steady-state engine operation comes from a dedicated thermal-to-electric power conversion system. This system uses waste heat from the engine (e.g., radiation absorbed in the vehicle shadow shield) as the thermal source. Finally, a conventional (i.e., normal-matter) LH_2 storage, feed, and injection system can be used; however, the anti-SH_2 will require magnetic levitation for storage, feed, and injection. Also, all components "seen" by the anti-SH_2 will require cooling to < 1 K as discussed above.

For this systems analysis, we will assume a "bottoms-up" approach, in which each subsystem is sized over a range of those parameters that determine the mass, power, etc. of that subsystem. Because of its importance in determining the overall engine thrust and thus vehicle acceleration, the various components will be related to the engine jet power (P_{jet}). Table 1 illustrates a preliminary list of potential systems and their relation to a complete propulsion system.

Component	Comments / Assumptions
ENGINE - GENERAL CHARACTERISTICS	
Engine - General	
Isp	John Callas (JPL); Exhaust Velocity (Ve) = Gc • Isp where Gc = 9.8 for Isp in lbf-s/lbm
Ve = Gc • Isp = F / M-DOT	F = Thrust, M-DOT = Propellant Mass Flow Rate
Total Engine JET Power	Pick a number consistent with expected final needs ±x10 ?
Thrust (F)	Pjet = 0.5 • Gc • Isp • F
Charged Pion ($\pi\pm$) Mass Flow Rate (M-DOT)	Gc • Isp = F / M-DOT
Fraction of Charged Pion / Total Initial H+Anti-H Mass	Callas
Total Initial H + Anti-H Mass Flow Rate (M-DOT total)	Total M-DOT = $\pi\pm$ M-DOT / Fraction
Power Distribution	
Gammas from Annihilation	Callas Equivalent M-DOT = M-DOT tot • Fraction P = M-DOT tot • c^2 • Fraction
Gammas from Neutral Pion (π^o) Decay	Callas Equivalent M-DOT = M-DOT tot • Fraction P = M-DOT tot • c^2 • Fraction
Total Gammas	Callas Equivalent M-DOT = M-DOT tot • Fraction P = M-DOT tot • c^2 • Fraction
Thermal (Waste)	Callas Equivalent M-DOT = M-DOT tot • Fraction P = M-DOT tot • c^2 • Fraction
Avaliable for Pjet	Callas Equivalent M-DOT = M-DOT tot • Fraction P = M-DOT tot • c^2 • Fraction
Actual Pjet	Fraction = Pjet / (M-DOT tot • c^2) See above See above
Calculation Check - Does Distribution add up ?	Add Fractions = 1 ? Add Equivalent M-DOT = M-DOT total ?
Overall System-Level Power (Energy) Flow	Account for all the various power (energy) sources (total annihilation power produced) and sinks (Pjet, radiation, thermal, electric power for mag. Nozzle magnets, refrigerators, power conversion, etc., etc., etc.) - Where does it all go ?
Efficiency	Callas
Pjet / Avaliable for Pjet	
Pjet / Total Power	
Particle Radiation Flux (Type, No.)	Used in sizing radiation shields
Gammas, etc.	Callas
Magnetic Nozzle	Callas
Field Strength	Callas
Magnet Dimensions	Callas
Power, Efficiency	
ENGINE COMPONENTS	
Magnetic Nozzle	
Magnet	
Field Strength	See above
Magnet Dimensions	See above
Current	Calculate based on Field Strength
Mass	Based on superconductor Ic Amps/cm^2
Power	
Energy	Startup energy (also shutdown dump energy)
Power	Steady-state operating power
Efficiency	Impacts waste heat requirement
Thermal Requirements (Temp.; Thermal Load)	Max Temp. allowed; Cooling Heat Load for "Cold" superconductor components
Shielding Requirements (Allowed Flux, Area, Thermal)	For components not protected by Vehicle Shadow Shield

Component	Comments / Assumptions
Shielding for Various Engine Components	Used to protect engine components not protected by Vehicle Shadow Shield
Total Radiation Flux (Type, No.)	See above
Flux onto Shield	Depends on Fraction of Total Flux intecepted by Shield (area)
Allowable Dose	Based on radiation flux and material's (e.g., superconductor) allowable dose
Dimensions	Thickness, area to protect engine components not protected by Vehicle Shadow Shield
Mass	Based on shielding material density
Temperature ("Hot" vs "Cold")	"Hot" shield will require radiator and may also impact heat load to other/nearby components; "Cold" shield will require refrigeration but minimizes heat load to other/nearby components
Waste Heat Reject Radiator for Various "Hot" Engine Components	
Waste Heat Power	Thermal power (waste heat, radiation, I^2R, etc.) into shield, structure, etc.
Temperature	Waste heat reject (radiator) max allowed temp for engine component (shield, structure, etc.) · May also impact heat load to other components
Area, Dimensions	Use 110% of area (10% contingency)
Mass	Use SOTA areal density or advanced radiator (liq oil drop, etc)
Thermal Control for Various "Cold" Engines Components	
Insulation (Type, area,density, mass)	TBD
Temperature	e.g., Superconductor max T allowed
Cooling Heat Load	Function of temp, insulation, radiation power not stopped by shield, heat soak from surroundings, etc.
Refrigeration System	Calculated below
Engine Structure	Structure to tie engine components together
Mass	Detailed mass estimate, or X% of mass of other engine components
Engine Gimbals (Mass, Power, Life->Redundancy)	Scale from existing
VEHICLE SHADOW SHIELD	
Shadow Shield	Used to protect rest of vehicle (not engine components)
Total Radiation Flux (Type, No.)	See above
Flux onto Shield	Depends on Fraction of Total Flux intecepted by Shield (area)
Allowable Dose	Based on radiation flux and materials (e.g., electronics) allowable dose
Dimensions	Thickness, area to shield rest of vehicle
Mass	Based on shielding material density
Temperature	"Hot" shield can be used as the thermal power source for the Thermal-to-Electric Power Conversion System
Waste Heat Reject Radiator	May not be needed if "Hot" shield used as thermal power source for the Thermal-to-Electric Power Conversion System
Waste Heat Power	Thermal power (radiation) into shield
Temperature	Waste heat reject (radiator) max allowed temp for shield material
Area, Dimensions	Use 110% of area (10% contingency)
Mass	Use SOTA areal density or advanced radiator (liq oil drop, etc)
CRUISE POWER	Used when engine off (during coast phase)
Cruise Power Reactor	
Power Needed	Based on prop. refrigeration and antimatter levitation systems electric power input + 10% (?) for housekeeping, etc.
Specific Mass	SP-100 class system 30 kg/kWe. Use MMW values if high enough. Add extra redundancy for 50-100 year lifetime
Mass	Base on specific mass and Pe
Dimensions (w/ Radiators)	Base on SP-100 class system
STARTUP POWER (ENERGY ?)	Used to start engine (also stop/cool-off period)
Startup Power (Energy) Reactor	Could be chemical, nuclear, energy-storage trickle-charged by cruise power reactor
Power (Energy ?) Needed	Based on engine startup electric power (energy) input - magnetic nozzle, feed system
Specific Mass	TBD (SP-100 class system ?)
Mass	Base on specific mass and Pe (or energy)
Dimensions (w/ Radiators)	TBD (SP-100 class system ?)

Component	Comments / Assumptions
POWER CONVERSION SYSTEM	Used when engine running to supply power for engine
Thermal-to-Electric Conversion	
Power Needed	Base on magnetic nozzle, storage and feed system, injector, refrigerators, other stuff ?
Input (Hot), Output (Cold) Temperatures	Higher Tin from dedicated flow loops in reactor/engine than from "hot" (warm ?) shadow shield ?
Cylce Used	Brayton, Stirling, Rankine - Choice may depend on hot/cold temps.
Specific Mass	Base on SP-100 power conversion ? - Depends on Tin/Tout (is power drawn from shadow shield -OR- from dedicated flow loops in reactor/engine ?)
Mass	Base on specific mass and Pe
Dimensions (w/ Radiators)	Base on SP-100 ?
PROPELLANT STORAGE AND FEED SYSTEM	
LH2 Tank	Conventional LH2 Tank ?
Propellant Density	0.070 g/cc (LH2)
Propellant Effective Density	Same as above; used to determine tank volume
Ullage	10% ?
Tank Material	Metal or Composite (large tanks) ?
Tank size, area, mass	Function of Mp, effective density, and ullage
Insulation (Type, area,density, mass)	MLI ?
Thermal Control (Type, mass)	Vapor Cooled Shield (VCS) ?
Storage Temperature	ca. 20 K for LH2
Cooling Heat Load	Function of temp, insulation, VCS, etc.
Pressurization	He or autogenous (low enough flow rate ?)
LH2 Feed System	Conventional LH2 feed system (Exclusive of LH2/Anti-SH2 Injector)
Valves, Filters, etc. Mass	Feed LH2 from Tank to Vaporizer and from Vaporizer to LH2/Anti-SH2 Injector
Insulation (Type, area,density, mass)	MLI ?
Storage Temperature	ca. 20 K for LH2
Cooling Heat Load	Function of temp, insulation, etc. - Also need to remove Tritium decay heat
LH2->Gas H2 Vaporizer Mass, Power	Power a function of LH2 M-Dot and ΔVvap - used to insure gasseous input to LH2/Anti-SH2 Injector
Anti-SH2 Tank	Conventional Tank Outer Shell (Minimum pressure differential)
Propellant Density	0.088 g/cc (Solid H2)
Propellant Effective Density	Much less than bulk solid density because propellant in form of swarm of solid pellets; used to determine tank volume
Ullage	>>>10% ? (to ensure that no pellets contact walls)
Tank Material	Metal or Composite (large tanks, NO OUTGASSING !) ?
Tank size, area, mass	Function of Mp, effective density, and ullage
Insulation (Type, area,density, mass)	MLI ?
Thermal Control (Type, mass)	Liq. He cooling coils ?
Storage Temperature	<< 1 K (Use Forward's estimate of vapor pressure)
Cooling Heat Load	Function of temp, insulation, annihilation radiation power due to vapor pressure, etc.
Radiation Flux (Type, No.)	Use Forward's estimate
Anti-SH2 Storage/Levitation Magnet(s)	Inside Anti-SH2 Tank
Thermal Control of Components Inside Tank	Any components inside the anti-SH2 tank will need to be maintained at the same temp. as the tank walls (see above) to prevent radiative heating of the anti-SH2 - There may be a significant trade-off in magnet field strength and placing the magnets (and their shields) inside the tank (i.e., T << 1 K and modest field) versus outside the tank (i.e., T ~100 K but high field)
Magnet	
Field Strength	Use Chris Paine (Brown U.) work - Assume max of 1-gee levitation force
Magnet Dimensions	Use Chris Paine (Brown U.) work
Current	Calculate based on Field Strength
Mass	Based on superconductor Ic Amps/cm^2
Power	
Energy	None; always on
Power	Steady-state operating power
Thermal Control	
Insulation (Type, area,density, mass)	TBD
Temperature	Superconductor max T allowed (ca. 100 K) if outside tank; otherwise, <<1 K if inside tank
Cooling Heat Load	Function of temp, insulation, radiation power not stopped by shield, etc.

Component	Comments / Assumptions
Shield	
Total Radiation Flux (Type, No.)	See above
Flux onto Shield	Depends on Fraction of Total Flux intecepted by Shield (area)
Magnet Allowable Dose	Based on radiation flux and materials (e.g., superconductor) allowable dose
Magnet Shield Dimensions	Thickness, area to protect magnet(s)
Magnet Shield Mass	Based on shielding material density
Shield Thermal Control	If magnets inside tank, need "cold" shield (<< 1 K); if magnets outside tank, can have "hot" shield (similar to Magnetic Nozzle Shield)
Magnet Shield Thermal Load Power	Thermal and radiation power into magnet shield, structure, etc.
Magnet Shield Temperature	"Hot" waste heat reject (radiator) max allowed temp (impacts heat load to magnet) if outside tank versus << 1 K if inside tank
"Hot" Magnet Shield	
Magnet Shield RadiatorArea, Dimensions	Use 110% of area (10% contingency)
Magnet Shield Radiator Mass	Use SOTA areal density or advanced radiator (liq oil drop, etc)
"Cold" Magnet Shield	
Refrigeration System Cooling Load	
Structure	Structure to tie magnet components together
Mass	Detailed mass estimate, or X% of mass of components (magnet, shield, radiator, etc.)
Anti-SH2 Feed System Lasers/Magnets & Levit. Mags.	System to extract individual Anti-SH2 pellets from tank and feed them into Engine (Exclusive of LH2/Anti-SH2 Injector)
Levitation Magnets System	Scaled-down version of Storage/Levitation Magnet(s)
Include various elements in Storage/Levitation Magnet(s)	
Extraction/Positioning System	Two possible options: Lasers (photon pressure pushes pellets) versus Electromagnetic (moving magnets or current loop in wire pushes/pulls pellets)
Laser Extraction/Positioning System Option	
Laser Beam Power	Power required to push anti-SH2 pellets against Storage/Levitation field
--> VERIFY THAT BEAM POWER TO PUSH PELLETS DOES NOT PRODUCE EXCESSIVE HEATING OF PELLET	
--> (Otherwise, may get radiation spike due to evaporation of anti-SH2)	
Laser Efficiency	Depends on laser type
Laser Electric Power	Pelectric = Pbeam / Eff.
Laser Mass	Include laser media, optics, movable optics (inside tank), electronics, etc.
Laser Thermal, Shield, Shield Thermal, Structure	Similar to Storage/Levitation Magnets Thermal, Shield, Shield Radiator, Structure
Electromagnetic Extraction/Positioning System Option	EM Field Generator could be current loop in (movable ?) wires (the technique used by Chris Paine) -OR- movable magnets
EM Field Generator Field Strength	EM Field required to push anti-SH2 pellets against Storage/Levitation field
EM Field Generator Power	Generate EM field and/or power to servo motors
EM Field Generator Mass	Include wires, magnets, actuators, movable parts (inside tank), electronics, etc.
EM Field Gen. Thermal, Shield, Shield Thermal, Structure	Similar to Storage/Levitation Magnets Thermal, Shield, Shield Radiator, Structure
LH2 / Anti-SH2 Injector	Injector in Engine
Assume similar to Anti-SH2 Feed System, but with more severe radiation environment in Engine	
Injector Thermal, Shield, Shield Radiator, Structure	Similar to Magnetic Nozzle Thermal, Shield, Shield Radiator, Structure
ACTIVE COOLING / REFRIGERATION SYSTEMS	Active cooling systems for superconductor magnets, LH2, Anti-SH2
Short-Life Cooling System(s)	Lifetime of Hours ? (Only while Engine operating)
Engine Magnetic Nozzle	ca. 100 K ?
LH2 Feed System	ca. 20 K ?
Anti-SH2 Feed System Lasers/Magnets	Magnets ca. 100 K, Anti-SH2 Walls << 1 K
LH2 / Anti-SH2 Injector	Magnets ca. 100 K, LH2 Walls ca. 20 K, Anti-SH2 Walls << 1 K
Long Life Cooling System(s)	Lifetime up to 100 Years (Full 40 LY Rendezvous Mission duration)
LH2 Tank	ca. 20 K ?
Anti-SH2 Tank	<< 1 K ?
Anti-SH2 Storage/Levitation Magnet(s)	Magnets ca. 100 K, Anti-SH2 Walls << 1 K

Component	Comments / Assumptions
OTHER VEHICLE SYSTEMS	
Power Managemant and Distribution (PMAD)	?? X% of power systems OR TBD kg/kWe ?
Structure	Structure to tie major components together - X% of total mass ?
Prop System C&DH/Avionics (Computers, etc.)	Guess arbitrary small amount for mass, electric power
Attitude Control	
CMG Wheels (Mass, Power, Life->Redundancy)	Scale from existing systems
RCS Thrusters (Mass, Power, Life->Redundancy)	N2H4 ??
Interstellar Debris Impact (Nose) Plate	0.5c debris impact could ruin your whole day . . . (Size from Daedalus)
PAYLOAD	Everything Else - 1 MT ?
Science	
Telecom, Power, C&DH-Avionics, Thermal, etc., etc.	