Antimatter Driven Sail for Deep Space Exploration

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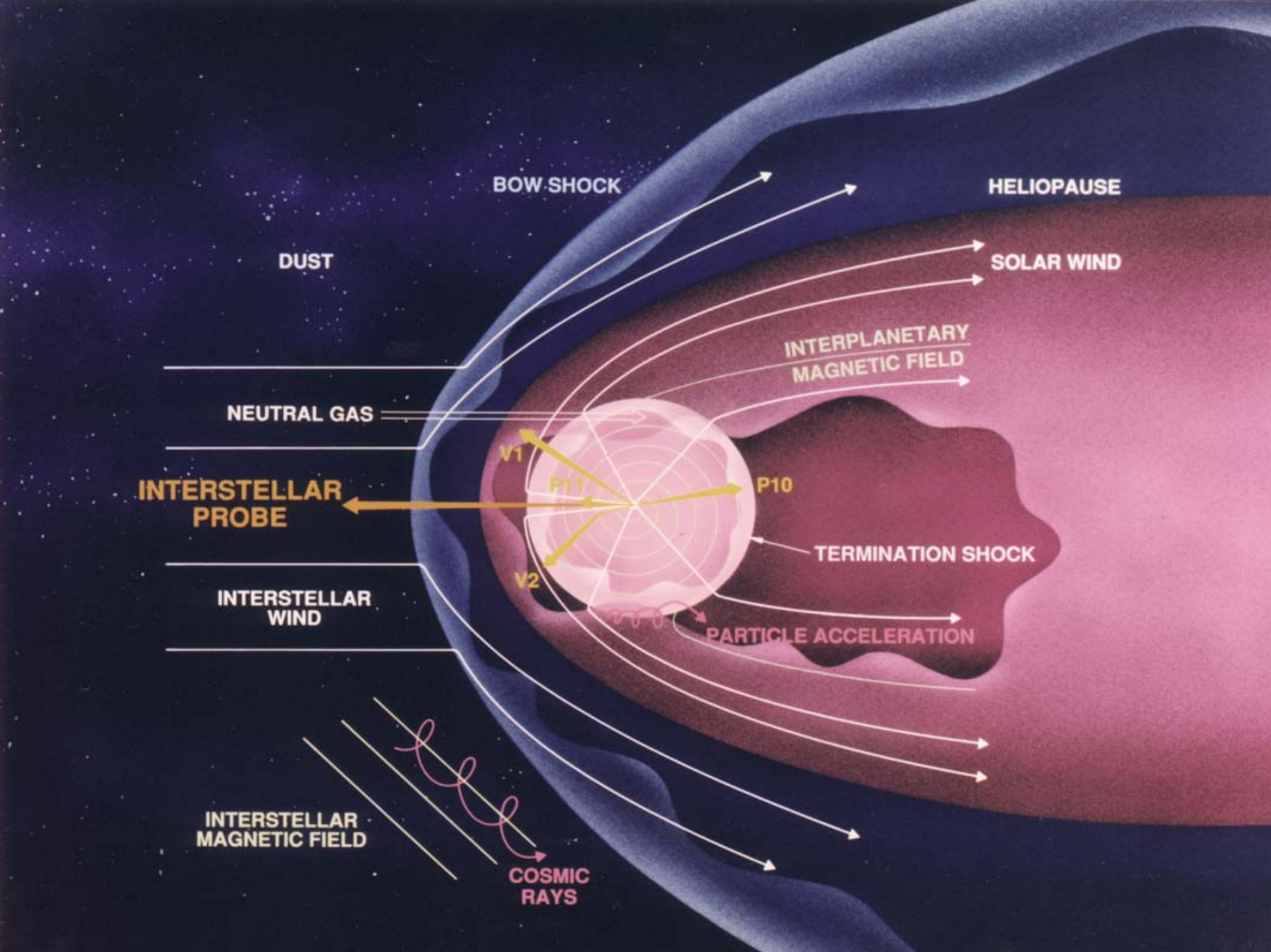
by Yuuji Kitahara

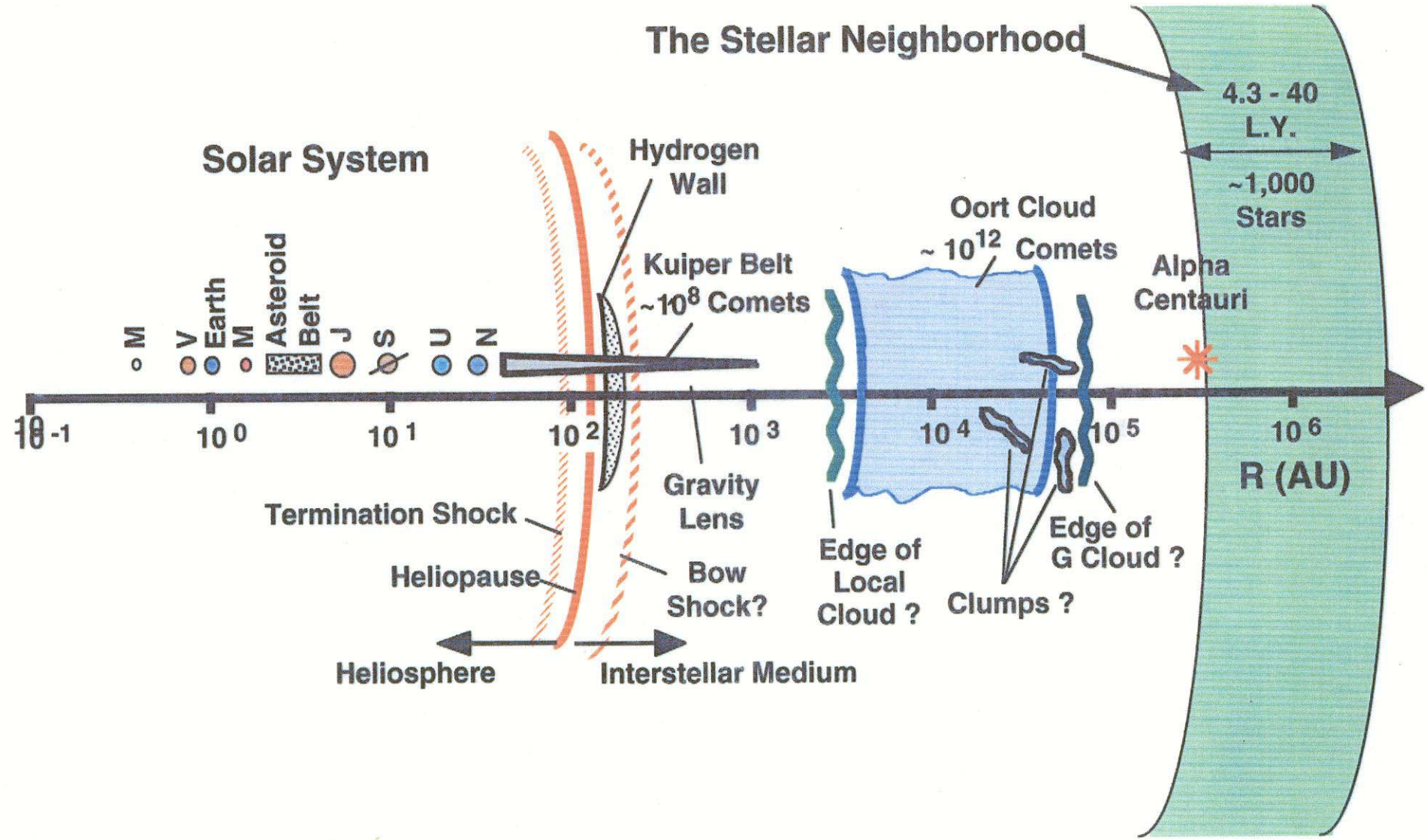
"Any technology being presented to you at this workshop will need at least one miracle in development in order to enable an interstellar mission" -

Dr. Steven D. Howe

Interstellar Robotics Missions for the 21st Century Workshop, JPL/Cal Tech, 1998


BOW SHOCK
HELIOPAUSE
DUST
SOLAR WIND
INTERPLANETARY
MAGNETIC FIELD
NEUTRAL GAS
V1
P11
P10
INTERSTELLAR
PROBE
TERMINATION SHOCK
V2
INTERSTELLAR
WIND
PARTICLE ACCELERATION
INTERSTELLAR
MAGNETIC FIELD
COSMIC
RAYS

SCALE OF THE HELIOSPHERE AND THE LOCAL INTERSTELLAR MEDIUM

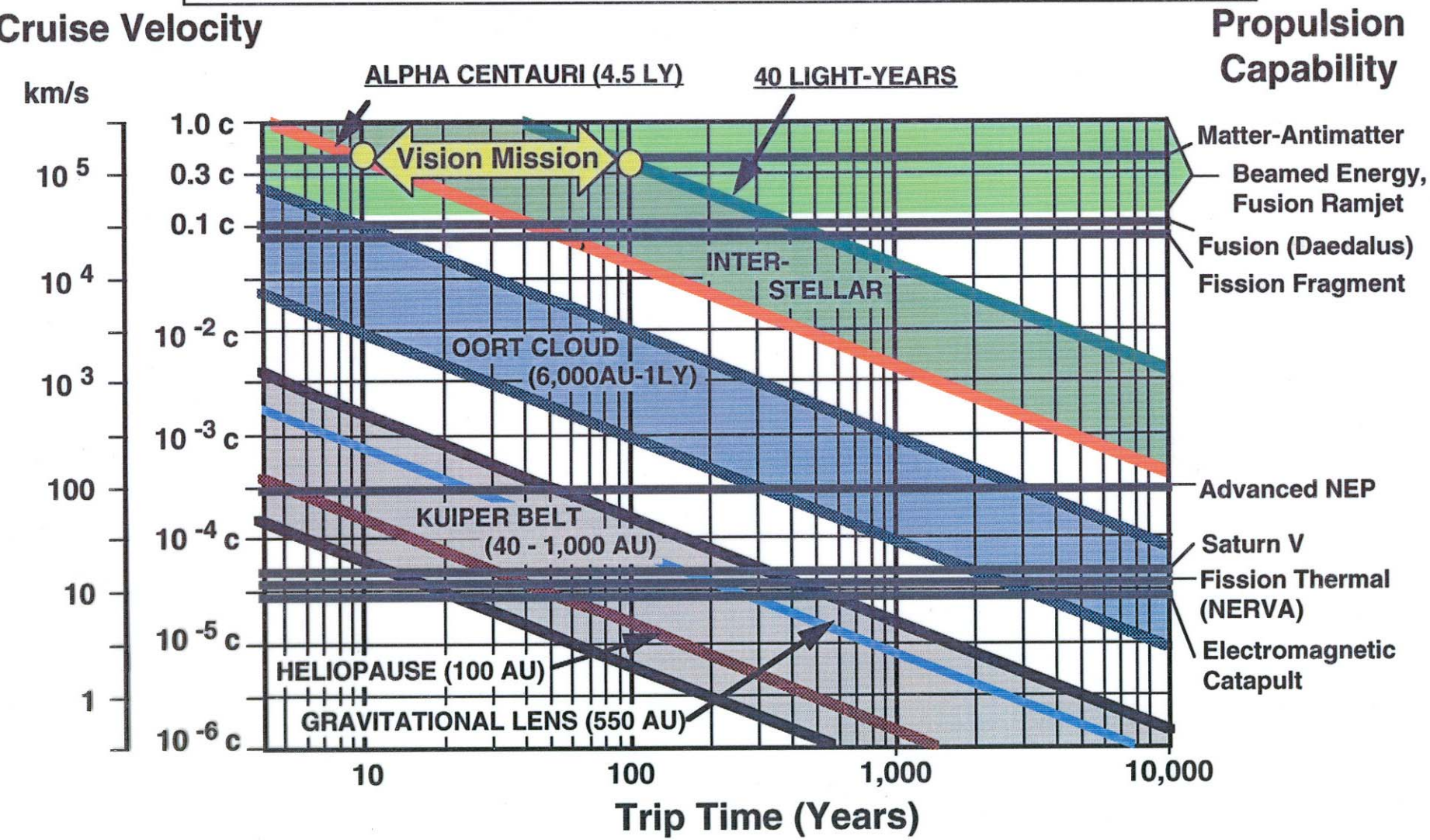


(Mewaldt,1998)

INTERSTELLAR & PRECURSOR MISSION

CRUISE VELOCITY & PROPULSION REQUIREMENTS

- Fission, Fusion, Matter-Antimatter Annihilation, or Beamed-Energy Sails Required for Interstellar Missions



Velocities Required for Deep Space Missions

MISSION	Velocity (km/s)	Energy Density (j/kg)
Kuiper Belt- 250 au - 10 yrs	117	6.8e09
Oort Cloud- 10,000 au- 40 yrs	1200	7.2e11
A Centauri – 270,000 au – 40 yrs	30,000	4.5e14

Energy Densities of Known Sources

Reaction	Specific Energy (MJ/kg)
Chemical	15
Fission (100%)	71E06
Fusion (100%)	750e06
Antimatter	90000e06

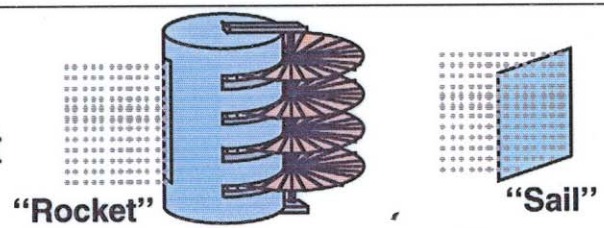
CANDIDATE PROPULSION SYSTEMS FOR INTERSTELLAR & PRECURSOR MISSIONS

JPL

- Need to achieve at least 0.1 c for interstellar missions
- Required energies and power levels as much as 200 times current output of human civilization (4×10^{20} J, 13 TW)
  - Apollo Saturn V at liftoff represented 0.5% of world power in 1969

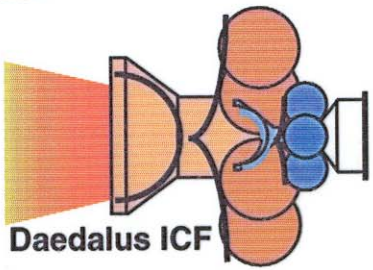
FISSION

Fission Fragment



FUSION

Inertial / Magnetic Confinement Fusion (ICF / MCF)

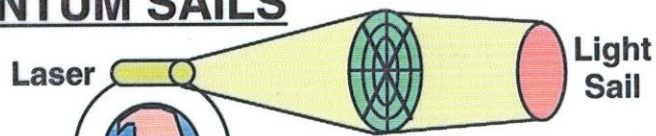


MATTER-ANTIMATTER

Beam-Core Antimatter Rocket

BEAMED MOMENTUM SAILS

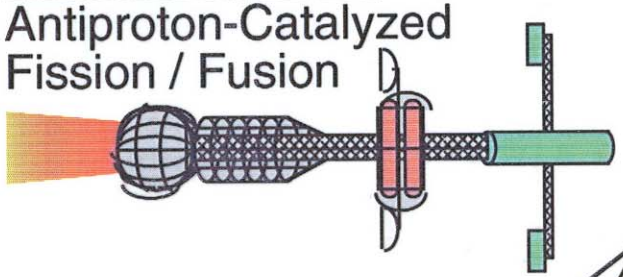
Laser Lightsail



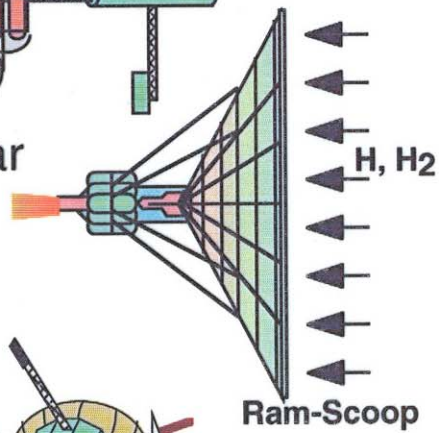
Relativistic Particle Beam / MagSail

COMBINATIONS

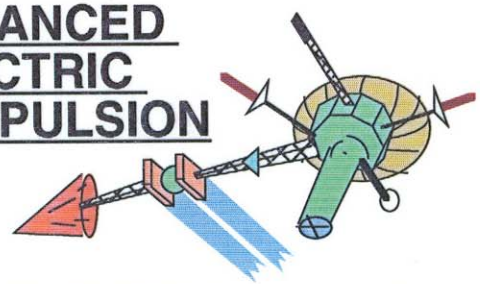
Antiproton-Catalyzed Fission / Fusion



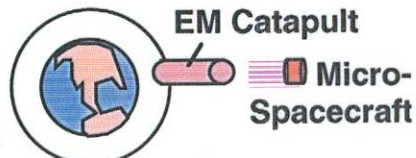
Bussard Interstellar Ramjet (Fusion)

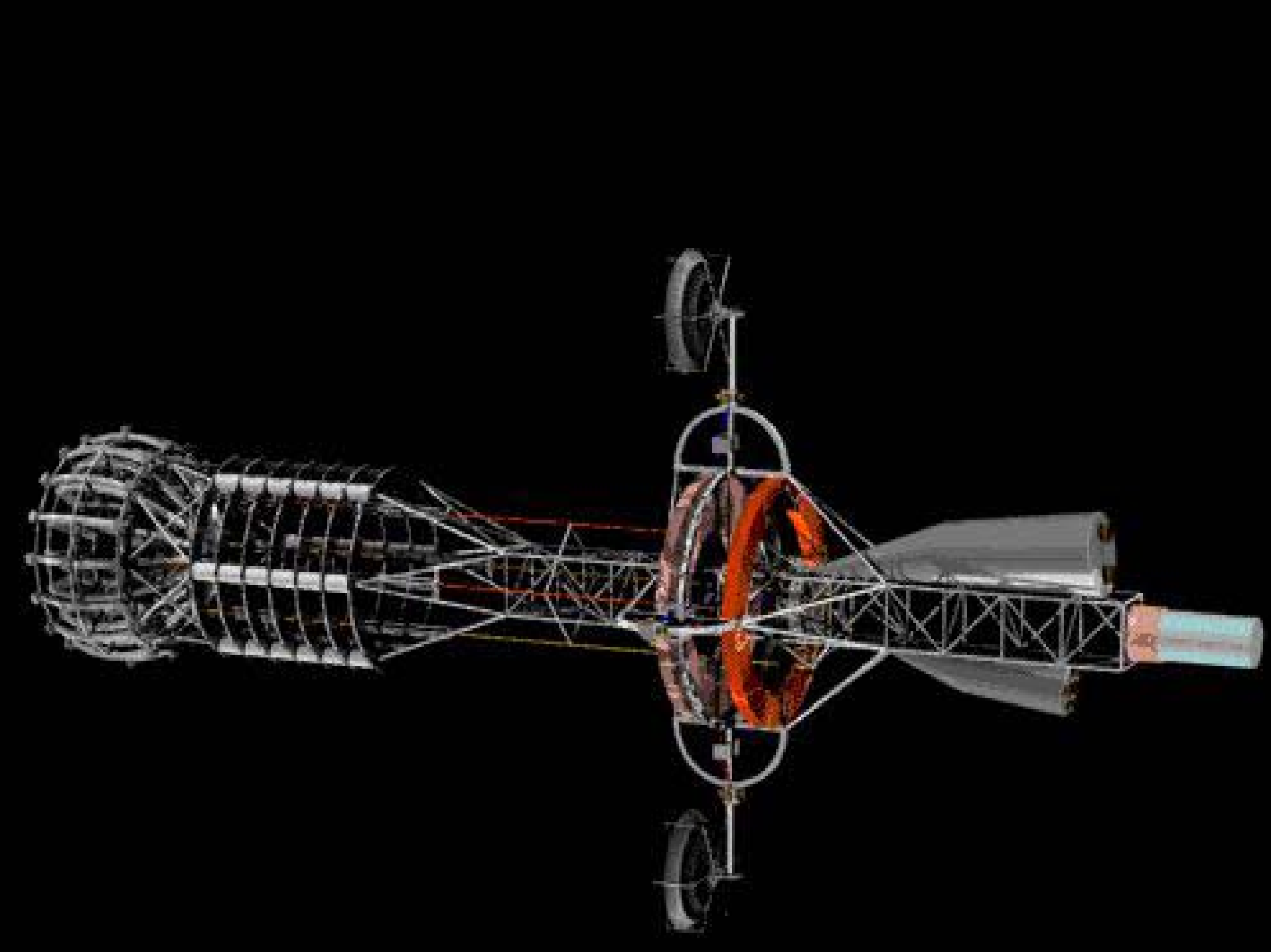


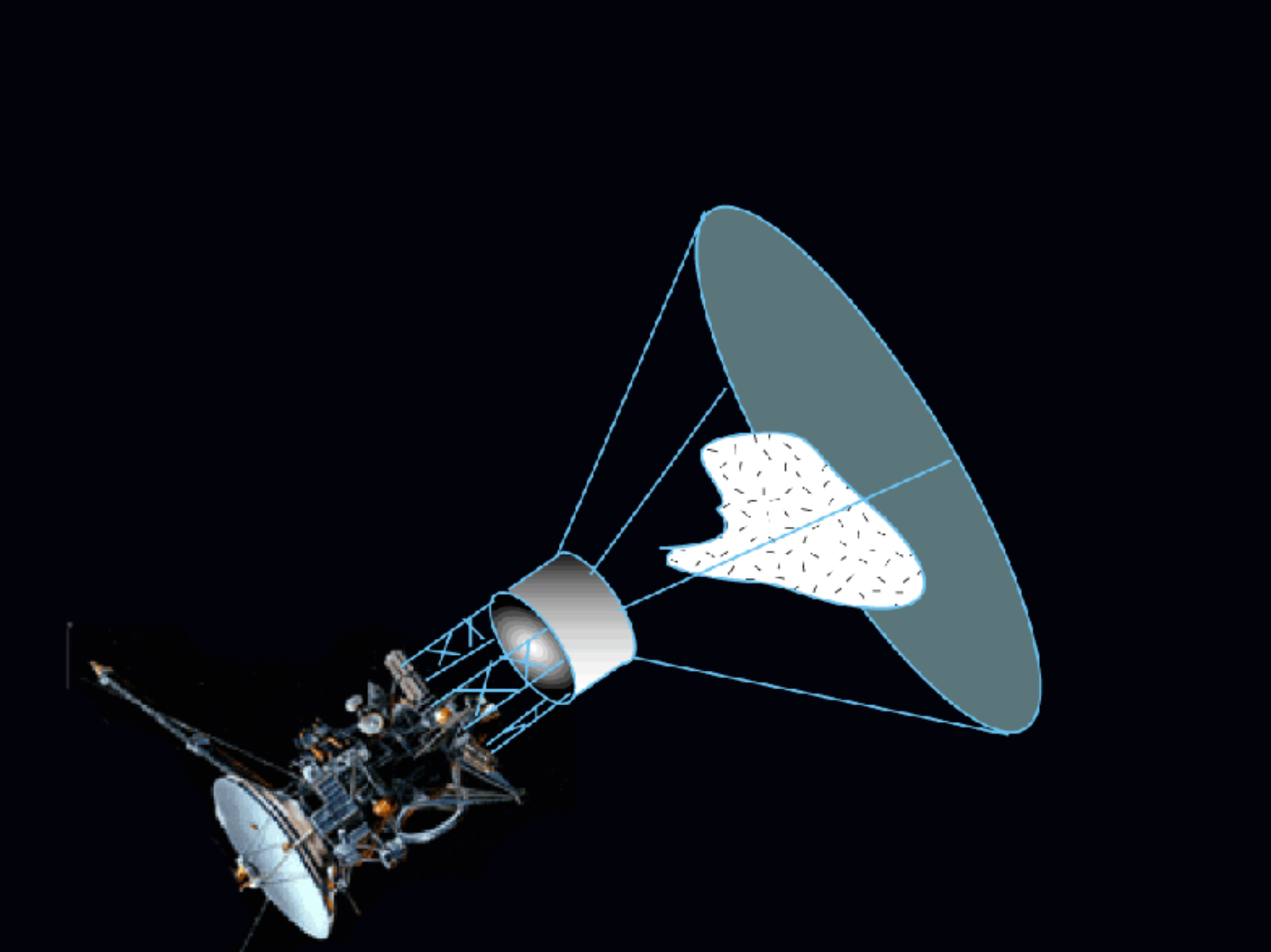
ADVANCED ELECTRIC PROPULSION



ELECTRO-MAGNETIC CATAPULTS





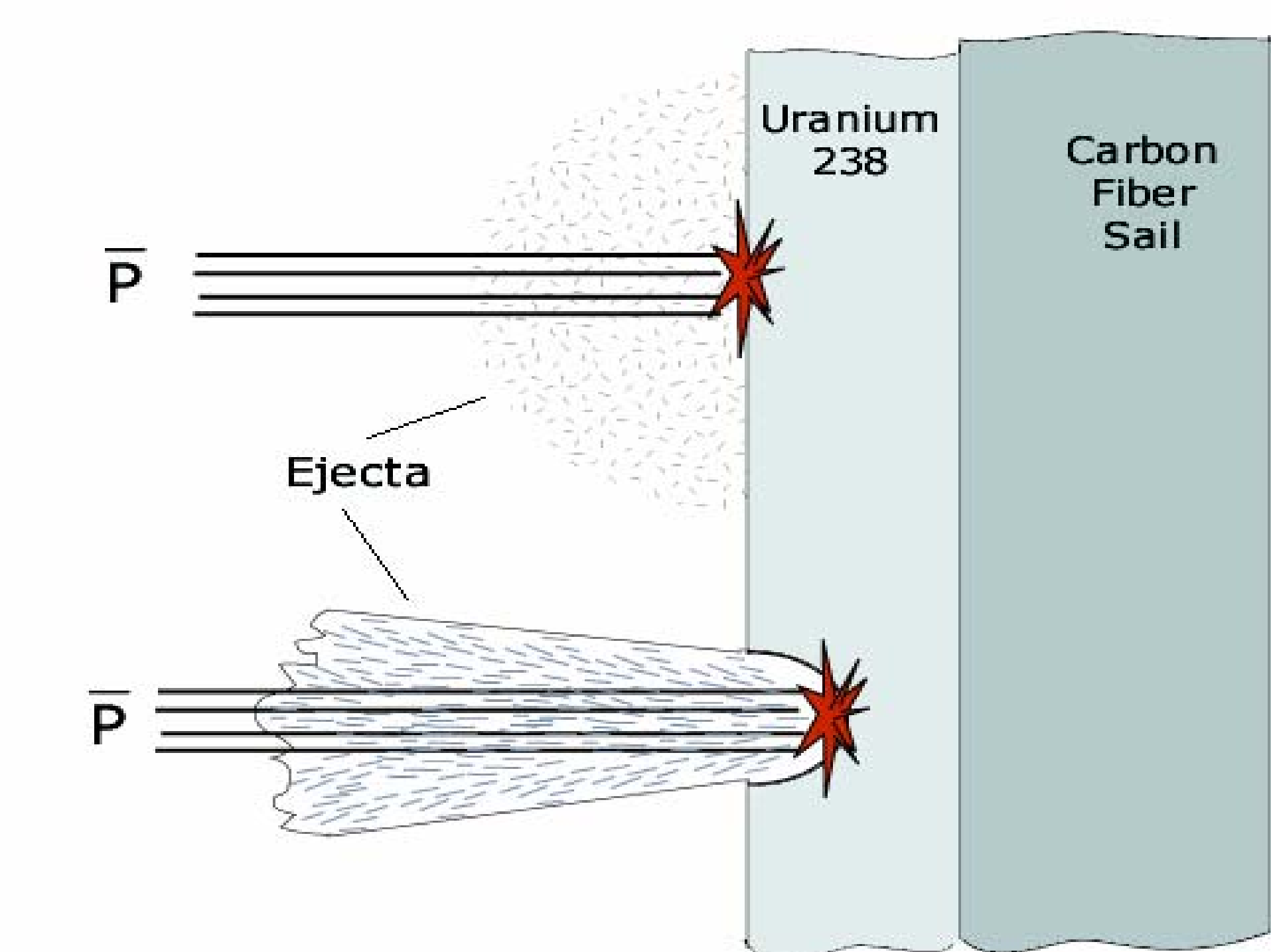


Antimatter Sail Concept

- Any conversion cycle to produce thrust that uses Local Thermodynamic Equilibrium (LET) will be heavy
- Antiprotons will induce fission in uranium with 100% efficiency
- Antiproton fission produces two products, (roughly Pd-111) each with near 1 MeV/amu
- A particle with 1MeV/amu has a velocity of around $1.38X10^{7}$ m/s
- Thus, an Isp of over 1 million seconds is possible

Specific Impulse

- For a given mission and ΔV, an optimum specific impulse exists for minimum energy consumption
- $V_{ex} = 0.6\ \Delta V_{mission}$
- $Mass_{final}/Mass_{initial} = .2$
- For ΔV of 117 km/s, V_{ex}=67 km/s (Isp=6800s)


Uranium
238
Carbon
Fiber
Sail
$\bar{P}$
Ejecta
$\bar{P}$

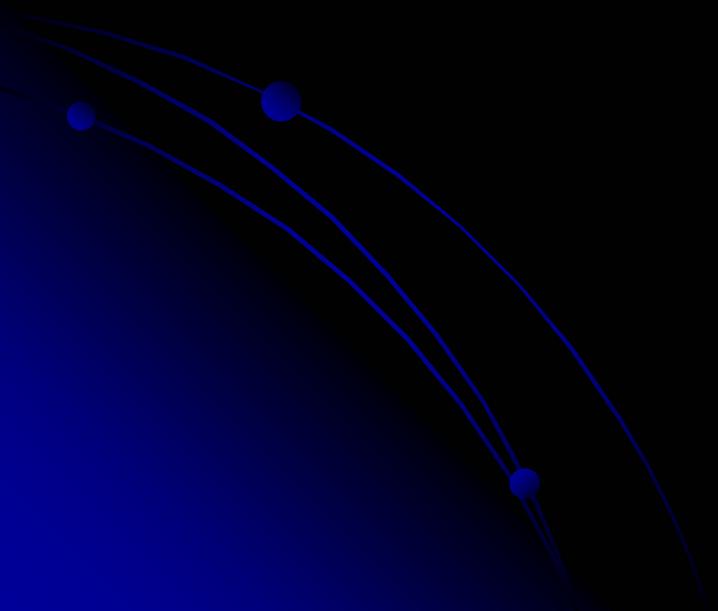
Variable Isp

- Sail concept may have the ability to adjust the Vex by varying the incident pbar energy or sail material
- Depositing the antiproton deep into the uranium may lead to multiple atom ejection resulting in increased thrust and reduced Isp
- Momentum is transferred by ingoing particle
- What is momentum from multi-atom burst?
- Mechanism causing burst is not known

Potential Advantages

- Extremely lightweight
- Does not require ultra thin sail material
- Ability to tack – course correct
- Ability to stop
- Variable acceleration
- Variable Isp

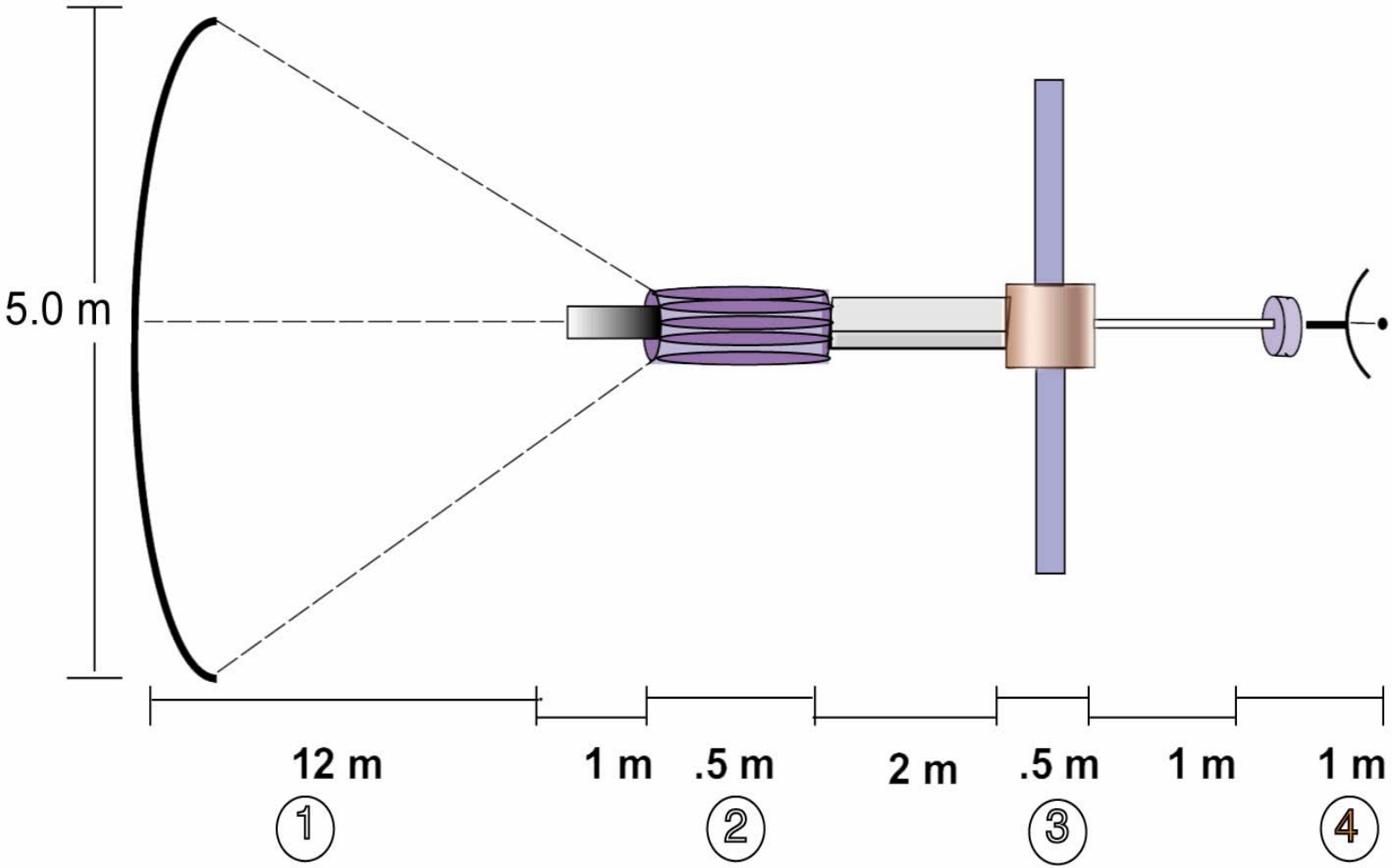
Phase I



Missions

- An interstellar mission is the eventual goal but is very tough
- Kuiper Belt in 10 years demonstrates the architecture
- Did not consider periapsis pumping, gravity boosts or more complex transfers- believe these are a 10-20% effect, i.e. 10km/s out of 100 km/s
- Assumed departure from 1AU orbit but beyond Earth orbit

Kuiper Belt Spacecraft



1. uranium coated carbon sail
2. solid H_2 bar flake storage units
3. electrical power supply, anti proton driven
4. 10 kg payload

Micro Payload

- Assume a total instrument payload of 10 kg including communications
- JPL report- Deutsch, Salvo, & Woerner – 10-50 kg by 2003
- JPL report – Hemmati & Lesh – ACLAIM: laser communications
- Interstellar Robotics Missions for the 21st Century Workshop, 1998- 10 kg

Sail Subsystem

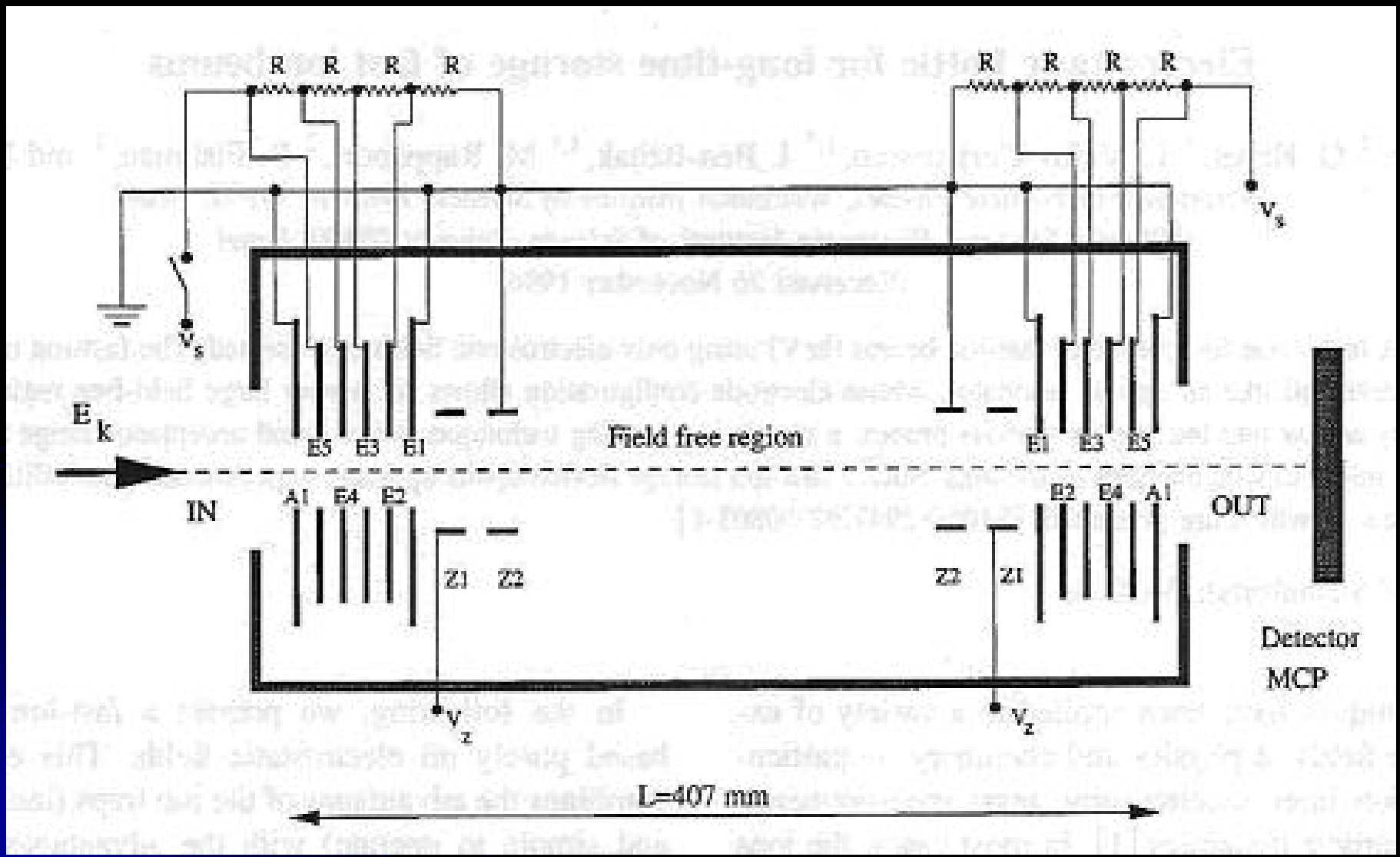
- Uranium coated carbon
- Carbon is thick enough to stop FF
- Examined the use of carbon only- Isp higher but not variable
- Key parameter is Nat- #atoms/fission
- Diameter dictated by pellet expansion
- Temperature dictates max pbar rate
- Acceleration dictated by solar gravity

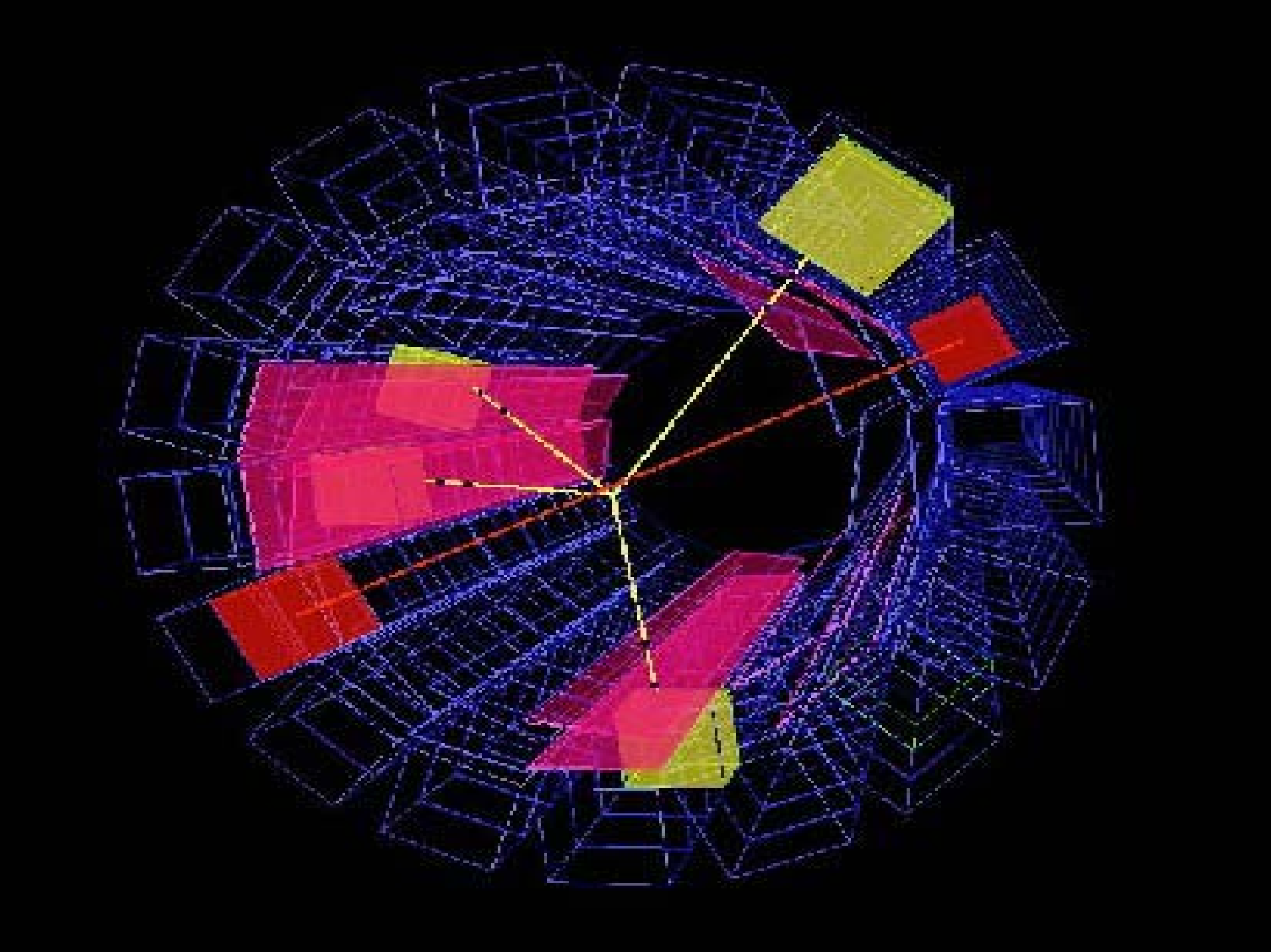
Sail Issues

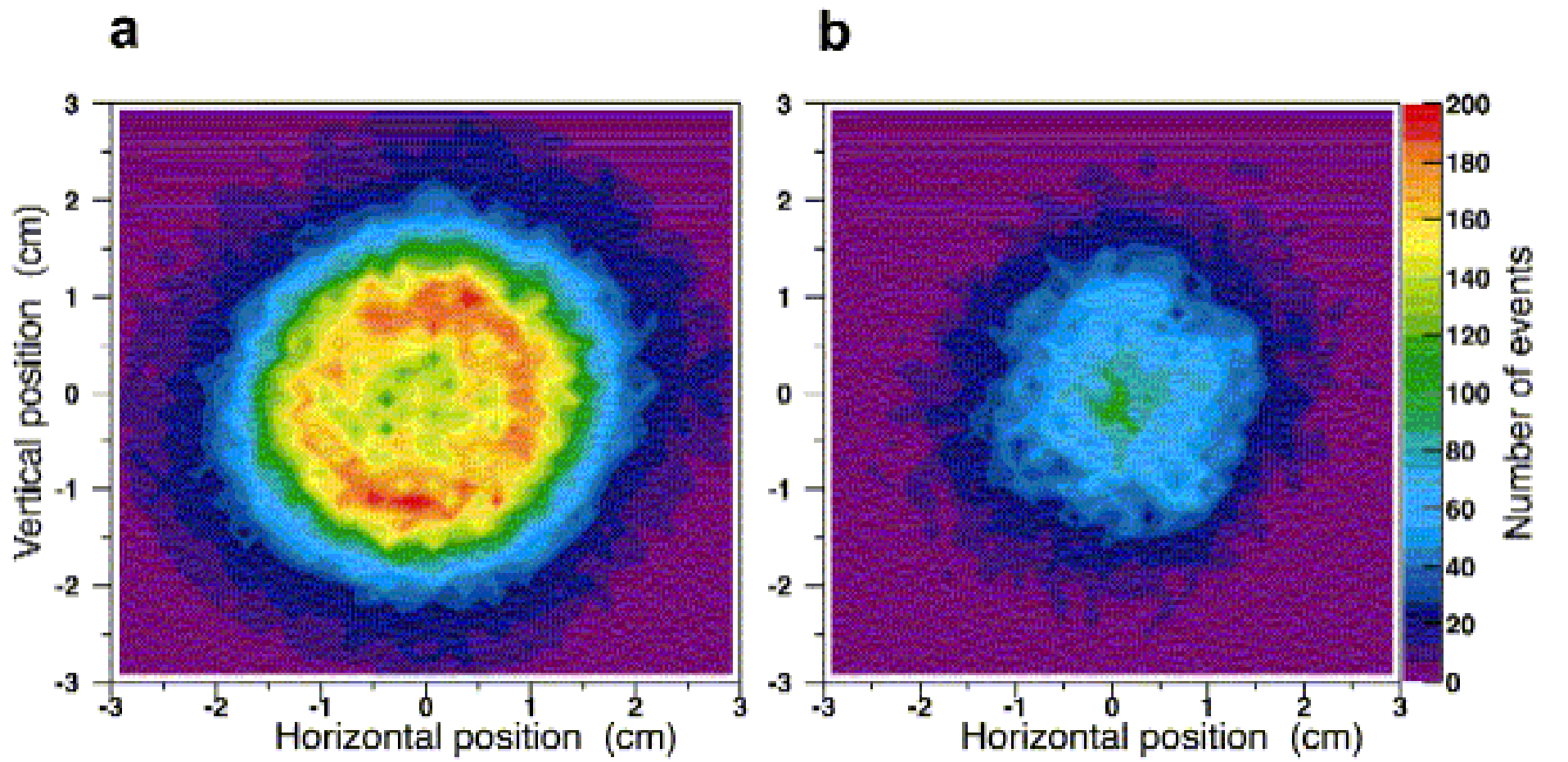
- Ejection and expansion of antihydrogen pellet
- Uniformity of deposition is not critical due to carbon recoil contribution
- Single most critical factor is Nat – if Nat is low then Isp is too high and mass goes up and thrust is insufficient.

Antimatter Storage

Antimatter Storage



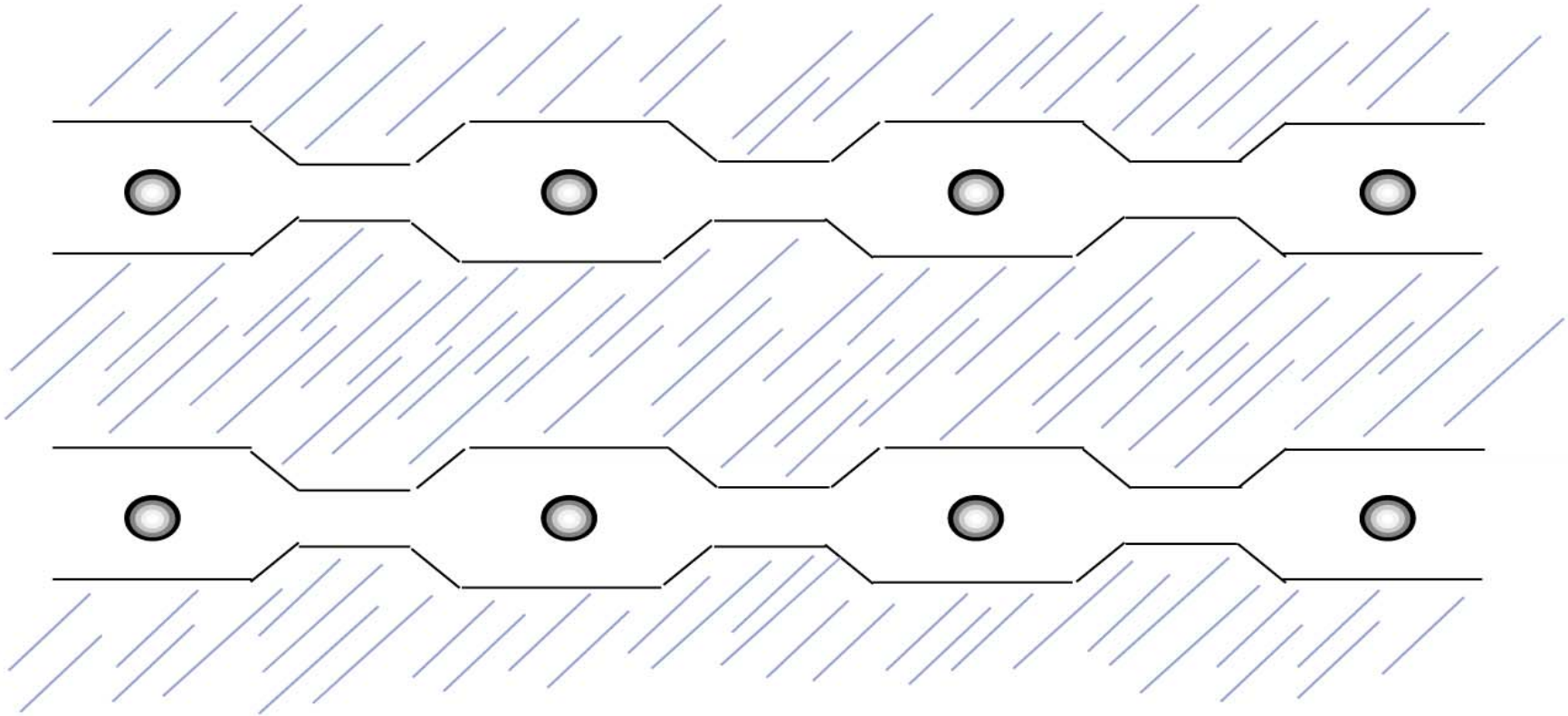



a
b
Vertical position (cm)
Horizontal position (cm)
Horizontal position (cm)
Number of events
3
2
1
0
-1
-2
-3
200
180
160
140
120
100
80
60
40
20
0

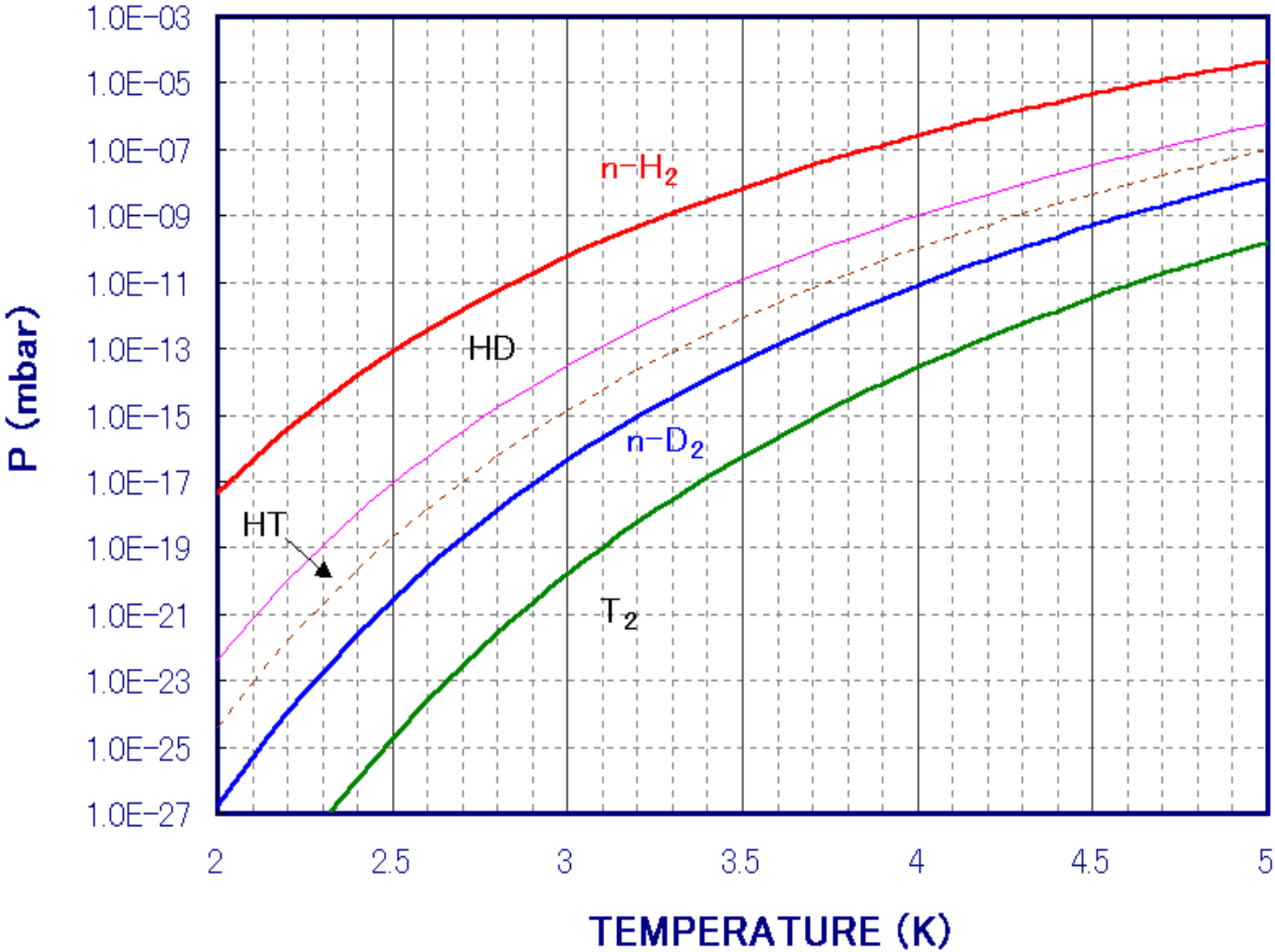
Antimatter Storage

- Solid antihydrogen has energy density
- Pbar + positron → Hbar (Athena-2002)
- Hbar + Hbar → H_2bar
- H_2bar → condensation → solid pellet
- Pellet + electrons → pellet^{n-}
- 10^{14} H_2bar has diameter of 160 μ
- Pellets^{n-} are held in an electrostatic trap array

Solid Antihydrogen Pellet Storage



[POC-Macroscopic Electrostatic Storage of Charged Pellet]


1.0E-03
1.0E-05
1.0E-07
1.0E-09
1.0E-11
1.0E-13
1.0E-15
1.0E-17
1.0E-19
1.0E-21
1.0E-23
1.0E-25
1.0E-27
P (mbar)
2
2.5
3
3.5
4
4.5
5
TEMPERATURE (K)
n-H2
HD
n-D2
HT
T2

Storage issues

- Creation of solid H_2 pellet
- Confinement of pellet in macro-scale electrostatic trap
- Containment of H_2bar in trap?
- Condensation rate and confinement
- Formation and control of pellet
- Evaporation of pellet

Power

- RTGs have 88 kg/kW
- Voyager has 400 W and 35 kg
- This would require 238 GJ of energy (13 mg pbars)
- Had to develop new power source
- Have on-board the highest energy source known
- Antimatter Fission Conversion (AFC)

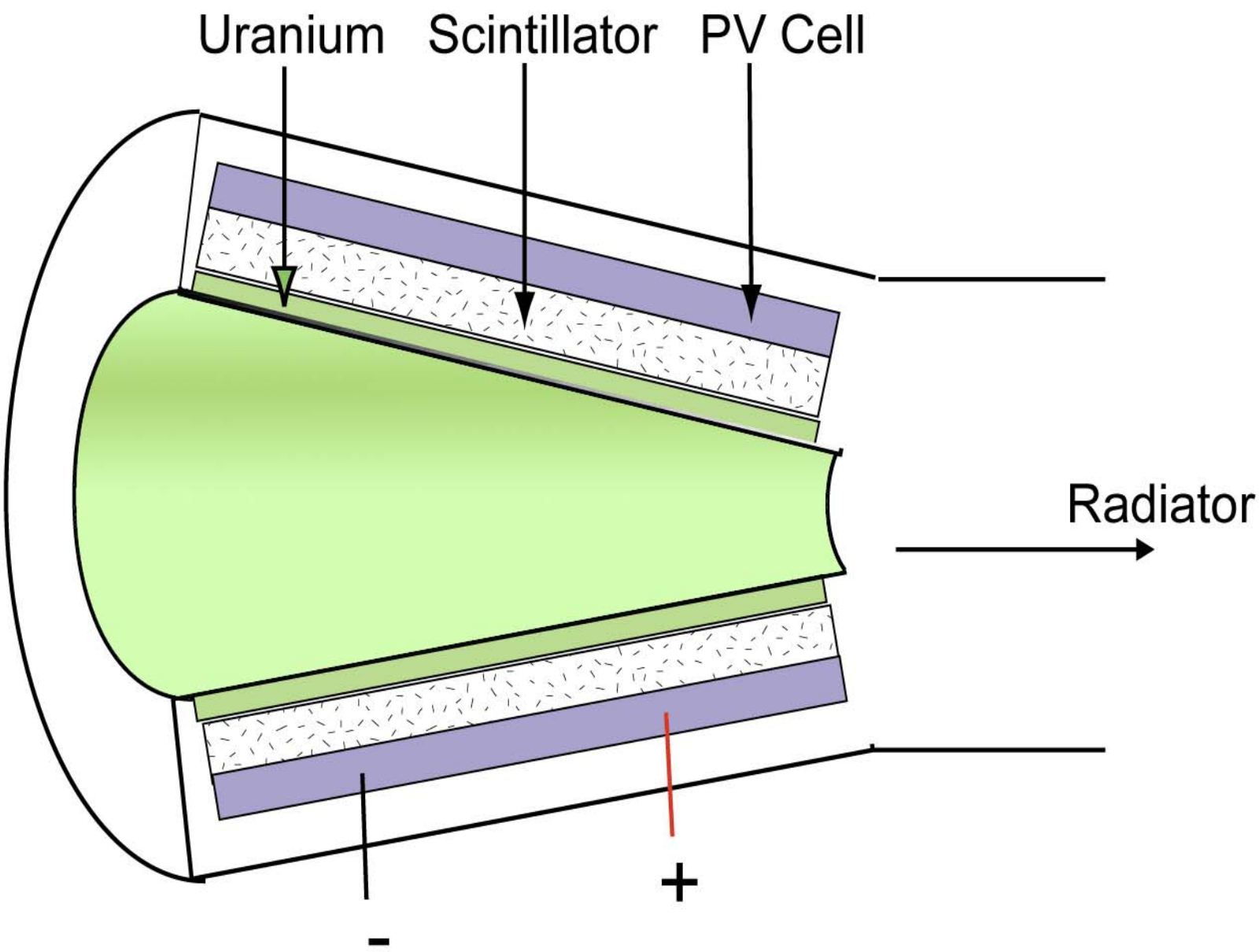
AFC

- Utilize antiprotons extracted from storage just as in the propulsion system
- Impact conical receptor consisting of uranium coated scintillator
- Scintillator tailored to emit photons “matched” to photo-voltaic (PV) cell

AFC

- Wavelength of scintillator determines conversion efficiency – 25 eV per photon required
- Must operate at high temperatures
- PV cell efficiencies and spectral response
- Conclude CdWO4 – high light output at 450 nm
- Total efficiency = .044
- Specific mass = 6.6 kg/kw

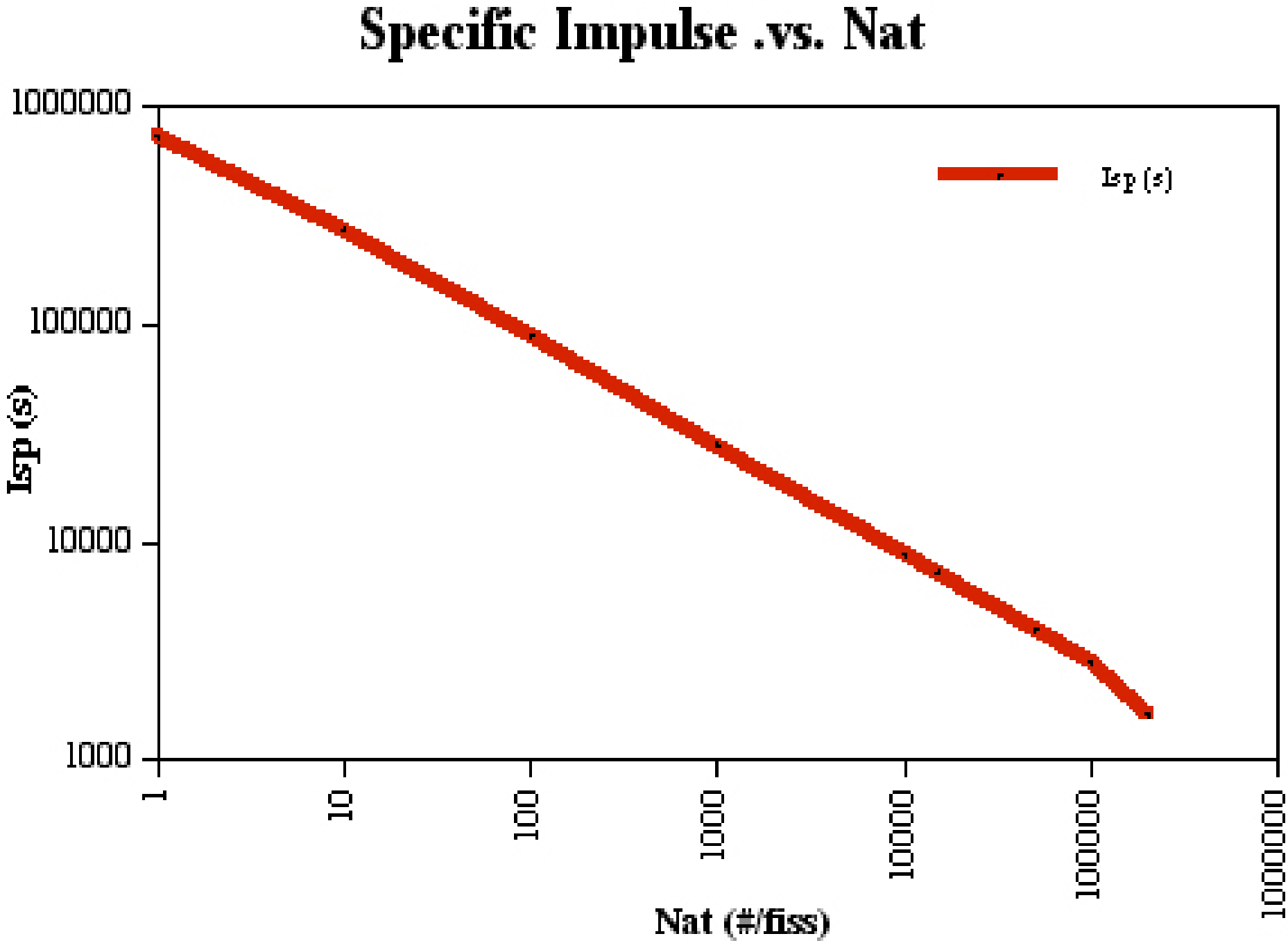
AFC Power Converter

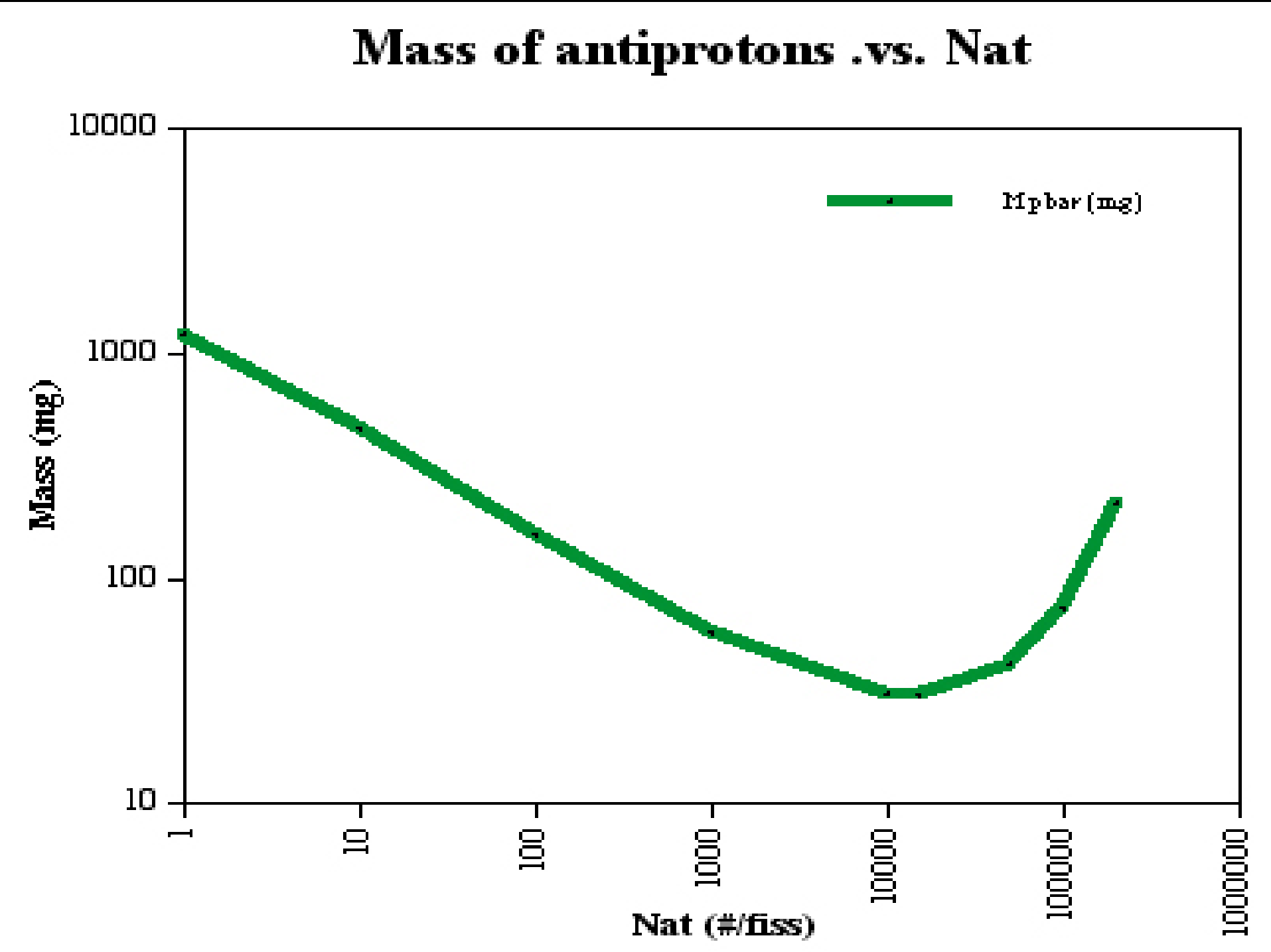


Power Issues

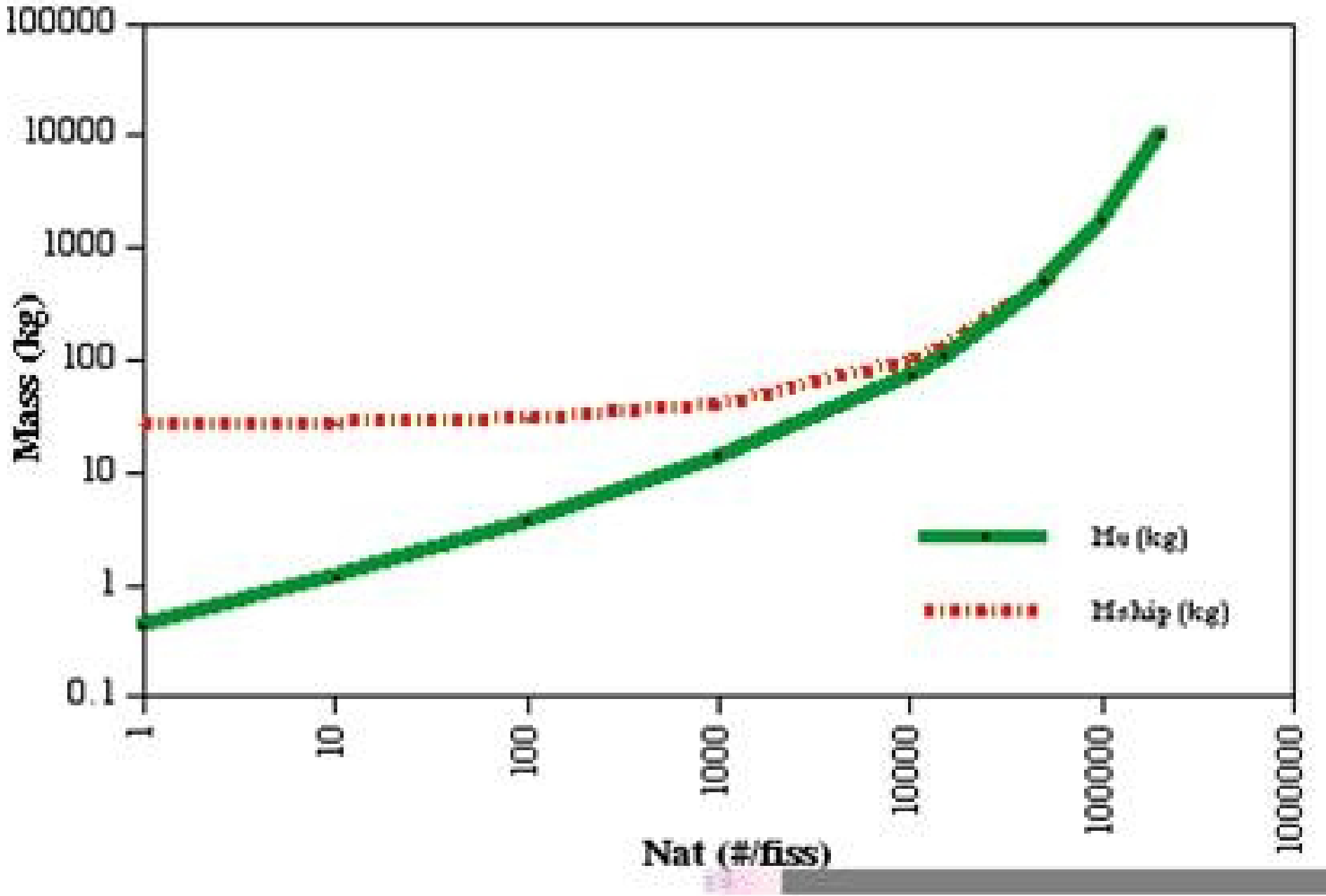
- AFC needs Proof-of-Concept (POC)
- Temperature dependence is crucial
- Coupling to radiator in pulsed mode
- Z^2 dependence could strongly impact design
- N_2 emits at 350 nm (5 ev): can we find a PV cell that works in that range? Potential efficiency = 8-10 %

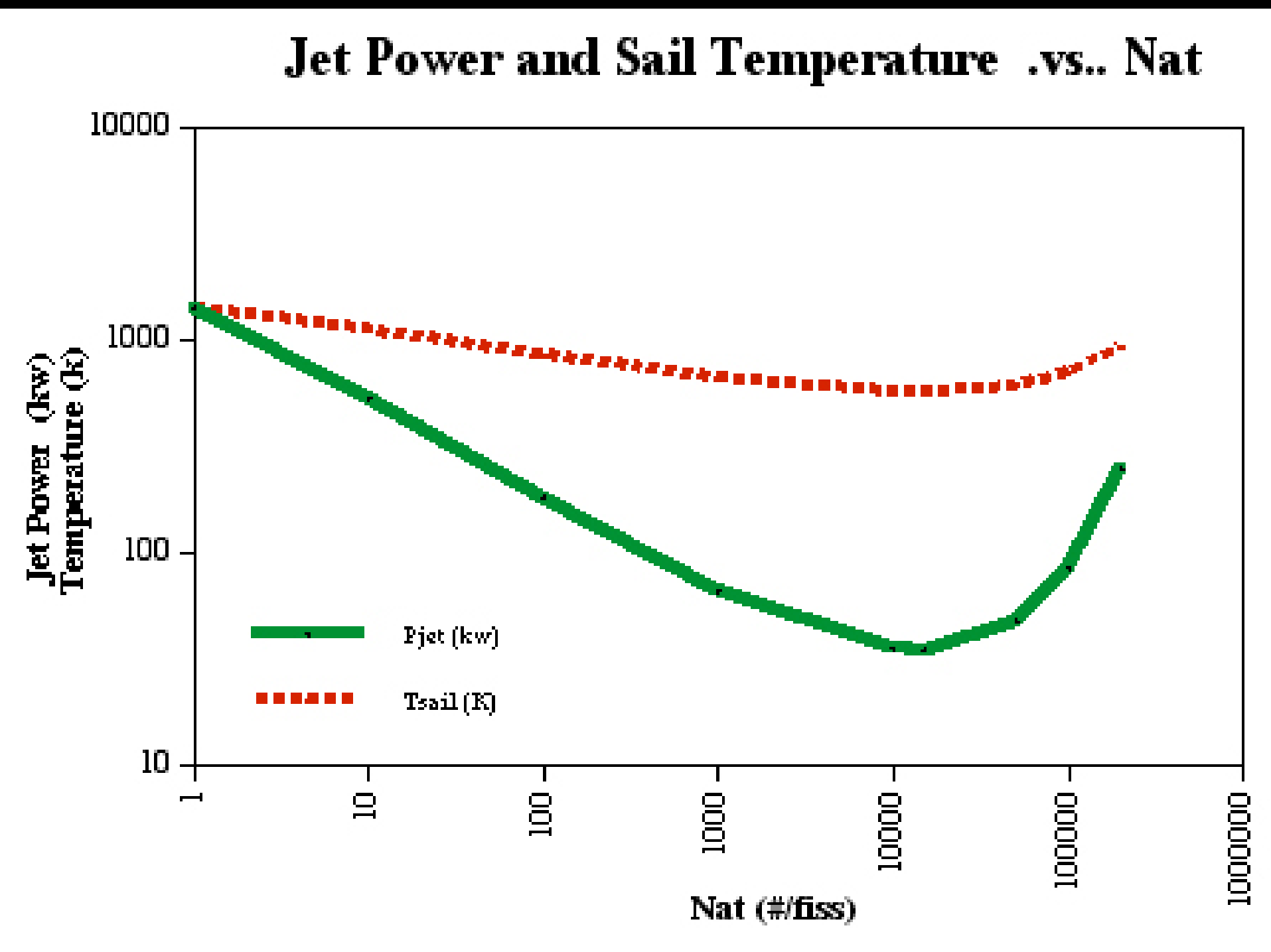
System Studies

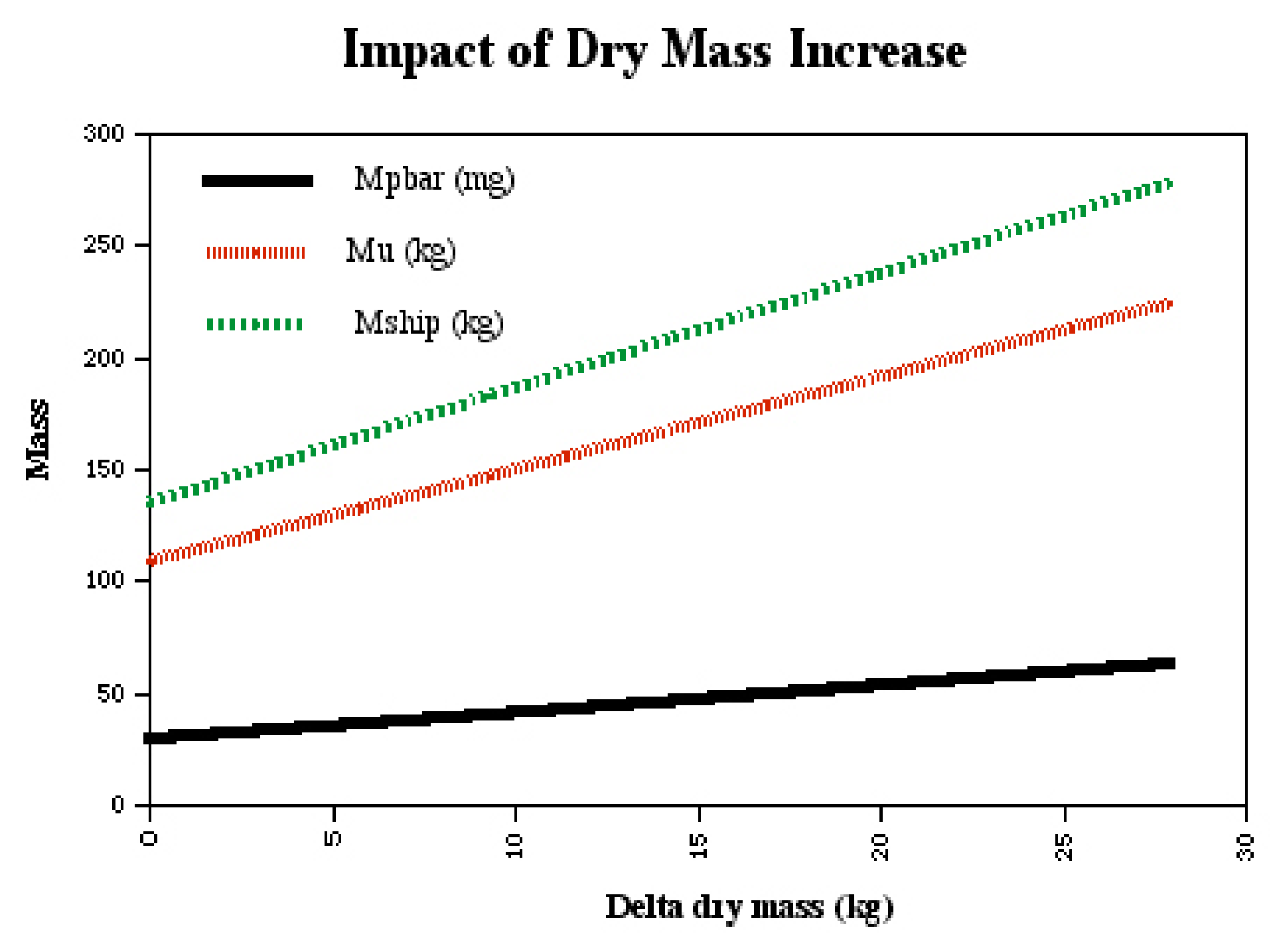

Specific Impulse .vs. Nat
1000000
100000
10000
1000
Isp (s)
Isp (s)
1
10
100
1000
10000
100000
1000000
10000000
Nat (#/fiss)


Mass of antiprotons .vs. Nat
10000
1000
100
10
Mass (mg)
Mpbar(mg)
1
10
100
1000
10000
100000
1000000
Nat (#/fiss)

Mass of fuel and ship .vs. Nat




Jet Power and Sail Temperature .vs.. Nat
10000
1000
100
10
Jet Power (kw)
Temperature (k)
Pjet (kw)
Tsail (K)
1
10
100
1000
10000
100000
1000000
Nat (#/fiss)


Impact of Dry Mass Increase
Mpbar (mg)
Mu (kg)
Mship (kg)
Mass
300
250
200
150
100
50
0
0
5
10
15
20
25
30
Delta dry mass (kg)

Technology roadmap

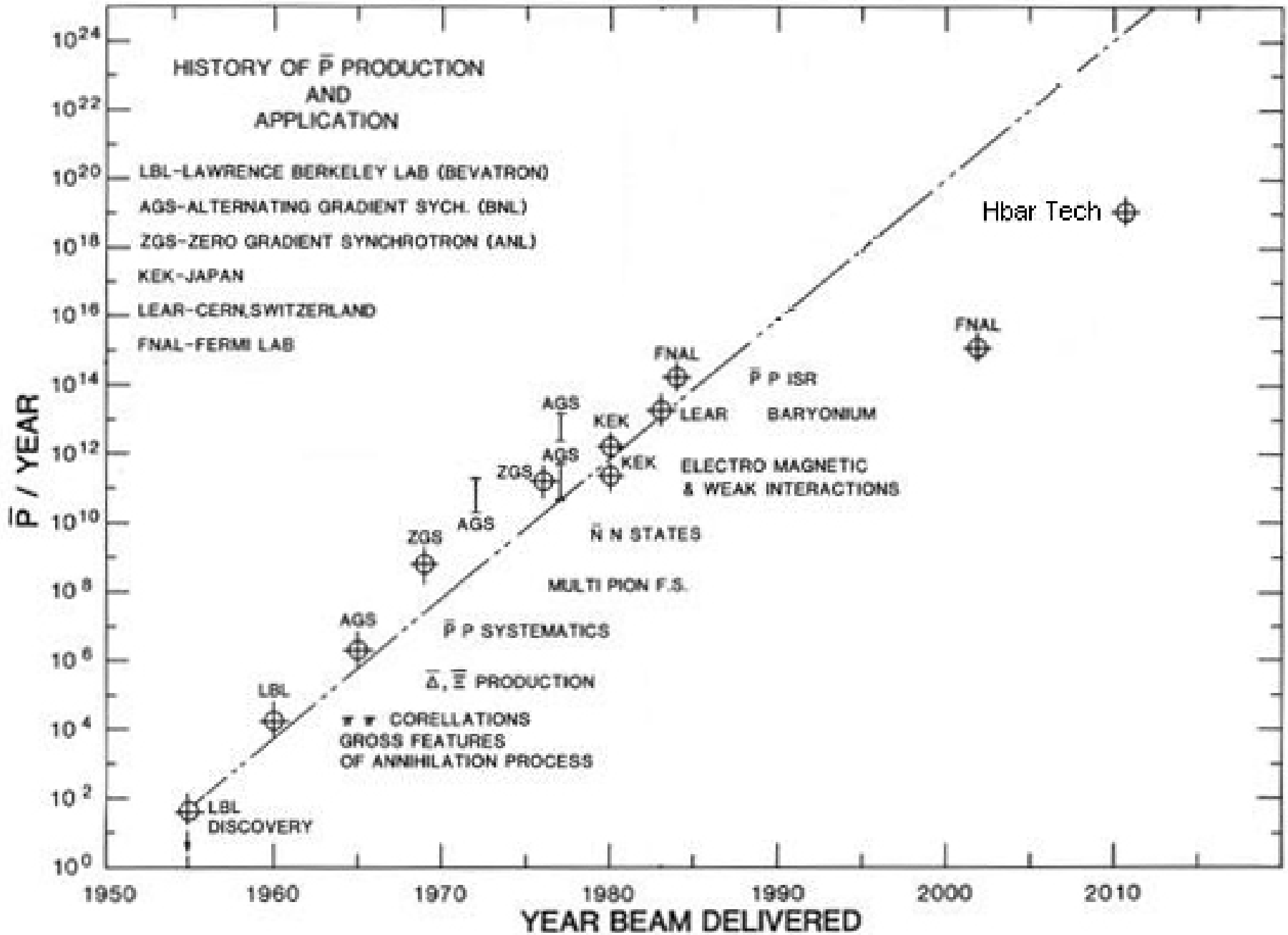
- Power
  - Demonstrate AFC on planar disks
  - Optimize for scintillator/PV Cell coupling
  - Evaluate temperature sensitivity
  - Evaluate hetero vs homogeneous
  - Demonstrate stand-alone prototype in space environment conditions

Technology Roadmap

- Antimatter Storage
  - Demonstrate storage in electrostatic trap
  - Demo storage of macro-particle
  - Demo accumulation of hydrogen molecules into pellets
  - Store pellets of SH_2 in solid state units
  - Improve formation rate of Hbar atoms
  - Demo formation of H_2bar molecules

Technology Roadmap

- Antimatter Production
  - Demonstrate deceleration of FNAL beam
  - Construct cooling ring at FNAL – 5e14/yr
  - Improve current and production at FNAL- X100 to 1000
  - Build new production machine optimized for pbar accumulation- 1-10 mg/yr


HISTORY OF $\bar{P}$ PRODUCTION
AND
APPLICATION
LBL-LAWRENCE BERKELEY LAB (BEVATRON)
AGS-ALTERNATING GRADIENT SYCH. (BNL)
ZGS-ZERO GRADIENT SYNCHROTRON (ANL)
KEK-JAPAN
LEAR-CERN,SWITZERLAND
FNAL-FERMI LAB
Hbar Tech
FNAL
FNAL
$\bar{P}$ P ISR
LEAR
BARYONIUM
AGS
KEK
AGS
KEK
ZGS
ELECTRO MAGNETIC
& WEAK INTERACTIONS
AGS
ZGS
$\bar{N}$ N STATES
MULTI PION F.S.
AGS
$\bar{P}$ P SYSTEMATICS
$\bar{\Delta}$, $\bar{\Xi}$ PRODUCTION
LBL
CORELLATIONS
GROSS FEATURES
OF ANNIHILATION PROCESS
LBL
DISCOVERY
10^{24}
10^{22}
10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
$\bar{P}$ / YEAR
1950
1960
1970
1980
1990
2000
2010
YEAR BEAM DELIVERED

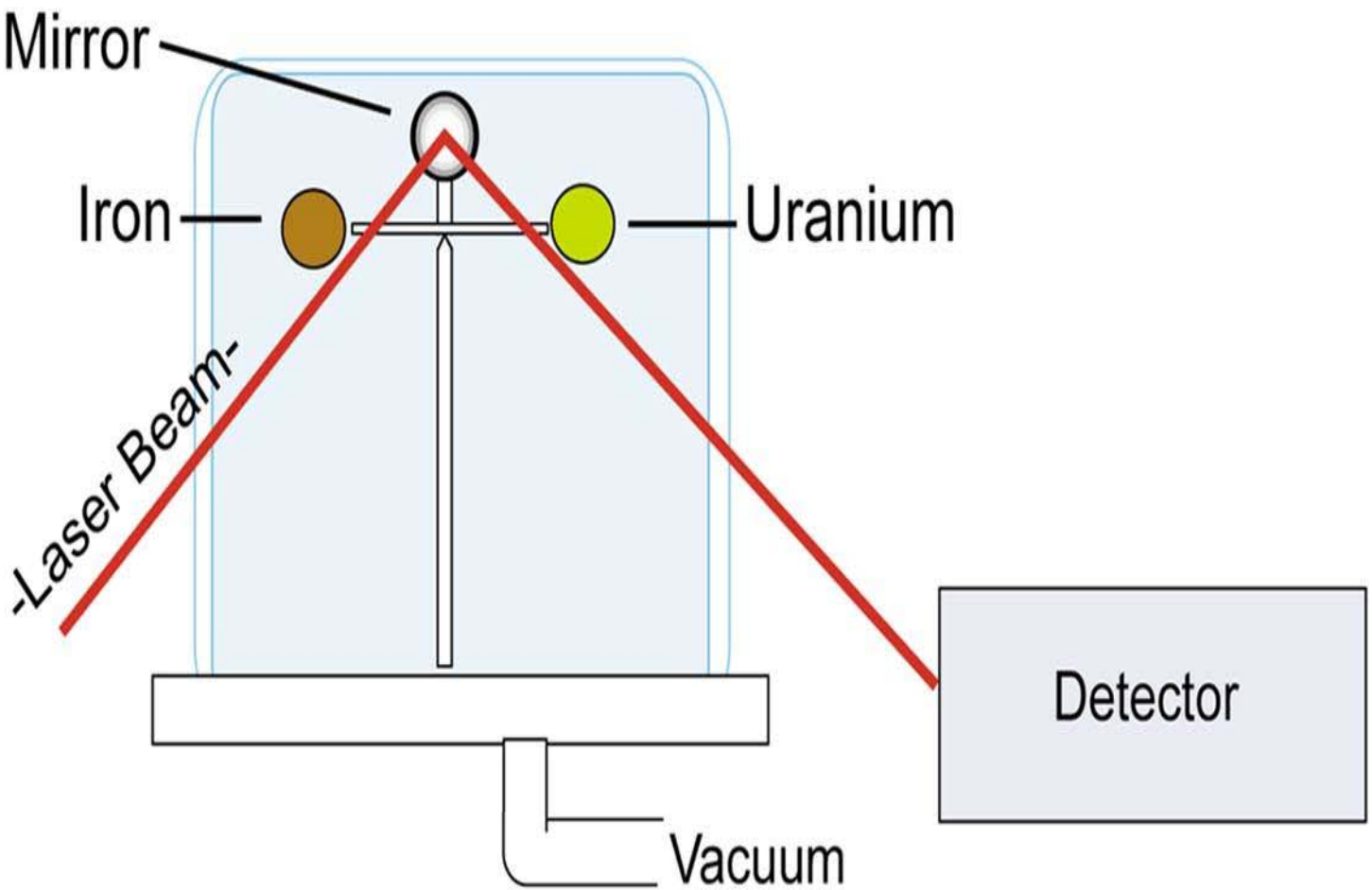
Phase II

- Detailed mission profiles with g assist, solar fly bys,
- Full technology path development
- Torsion experiment – measure Δp; ejecta
- AFC Power cell demonstration
- Storage – electrostatic trap demo of pellet; pellet formation and vaporization

“Nat” is the Key

- Two experiments in the past indicate a range of 10,000 – 100,000 atoms/fission
- NOT surface fission but volumetric
- NOT fast fission but SF
- Ejection mechanism may depend on light fragment/heavy fragment of normal fission
- Real question is what is the momentum transferred by the ejecta cloud

POC-Torsion Balance Experiment



Summary

- Kuiper Belt mission in 10 years is possible with mg quantities of antihydrogen- not gm to kg
- Sail concept appears feasible IF Nat is above 1000
- New power concept may be applicable to intrasolar system missions within next decade
- Pbar sail is the lowest mass/lowest energy consuming concept yet developed
- POCs can be performed in Phase II
- Concept may allow interstellar mission to be launched within next 2 decades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