Space Electric Propulsion in the 22nd Century

Some Speculations
by

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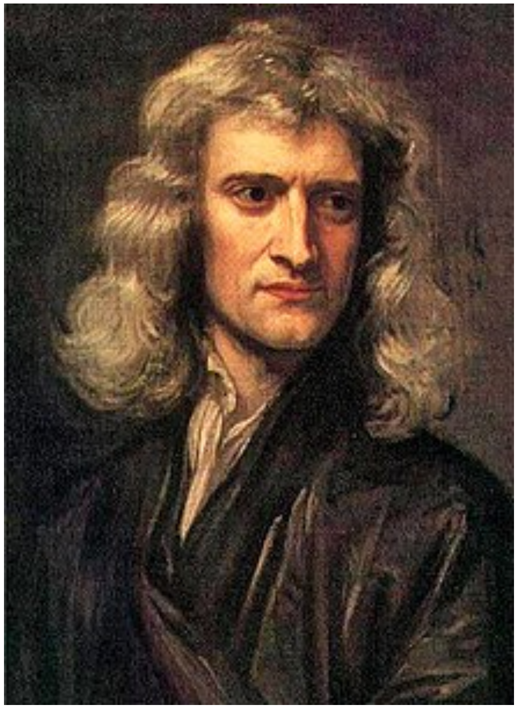
The Solar System with ΔV = 40km/s

Destination with capture	Radius from Sun (AU)	Transfer time (months)
Mars	1.52	2.1
Jupiter	5.2	11.1
Saturn	9.54	21.7 (1.8 Y)
Uranus	19.18	47.4 (4.0 Y)
Neptune	30.06	76.6 (6.4 Y)
Pluto	39.52	102.6 (8.6 Y)
100 AU	100	270 (22.5 Y)

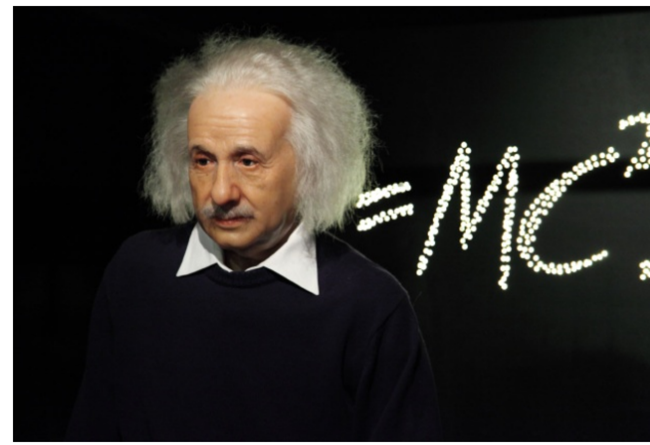
This is why we need electric propulsion

Origins



Sir Isaac Newton
1643 – 1727
Equations of motion
(energy & momentum)
Gravitation

Robert Goddard
1882 – 1945
Speculations on Space
Electric Propulsion



Albert Einstein
1879 – 1955
Mass equivalent of energy
(plus other very clever stuff!)

Space Electric Propulsion is finally here

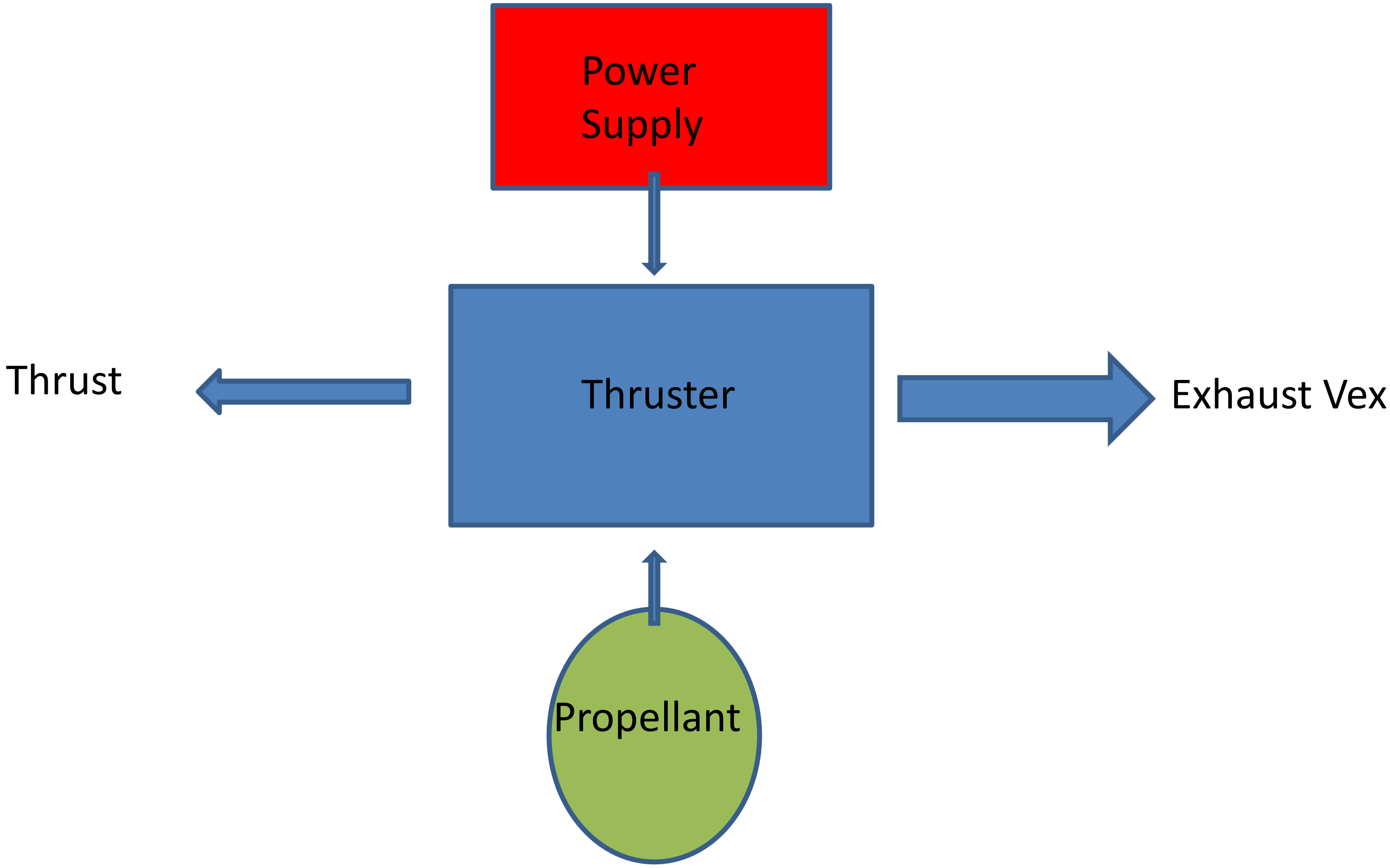
It’s been a long tedious route with the first ideas during the fist three decades of the twentieth century, their evolution in the 1950s, their development in the 1960s and flight tests in the 1970s. The true applications had to wait for the twenty first century.

Why has it taken so long? caution, lifetime, power supplies

Even today, applications are only at kilowatt levels and deep space missions are still dominated by chemical propulsion.

In this presentation we will look at the prospects for this field to expand to deliver ready access to the solar system, and even the nearby stars

Back to Basics for a Moment



Minimum Installed Energy

final mass $M_{f,}$ mission velocity ΔV, efficiency η and mass ratio R

constant exhaust velocity (Vex =const)

$$E = \frac{M_f}{2\eta} \Delta V^2 \frac{R-1}{Ln^2(R)}$$

optimum R=4.93
Vex = 0.6268 ΔV

variable exhaust velocity (Vex=k/M)

$$E = \frac{M_f}{2\eta} \Delta V^2 \frac{R}{R-1}$$

same as above for R=2.838
Vex_{max} = 1.544 ΔV
Vex_{min} = .5756 ΔV

Initial mass for variable Vex is 0.5756 times the mass for fixed Vex

Therefore:-

For energetic missions variable exhaust velocity is highly desirable

For (50km/s < ΔV < 100km/s) we would want the same thruster to deliver (27km/s < V_{ex} < 154km/s)

However:-

For large vehicles with M_f > 40t the propellant should be plentiful, non-contaminating and chemically inert. Argon is the obvious choice with accel voltages from 150V to 5000V for single ionisation.

Although the 1st ionisation potential is only 15.68eV the current cost/ion is more like 200eV so that more efficient ionisation techniques are desirable. Argon is particularly difficult in this respect.

Producing Thrust

There many ways of coupling the electrical energy into the propellant and accelerating it as a jet to produce thrust:-

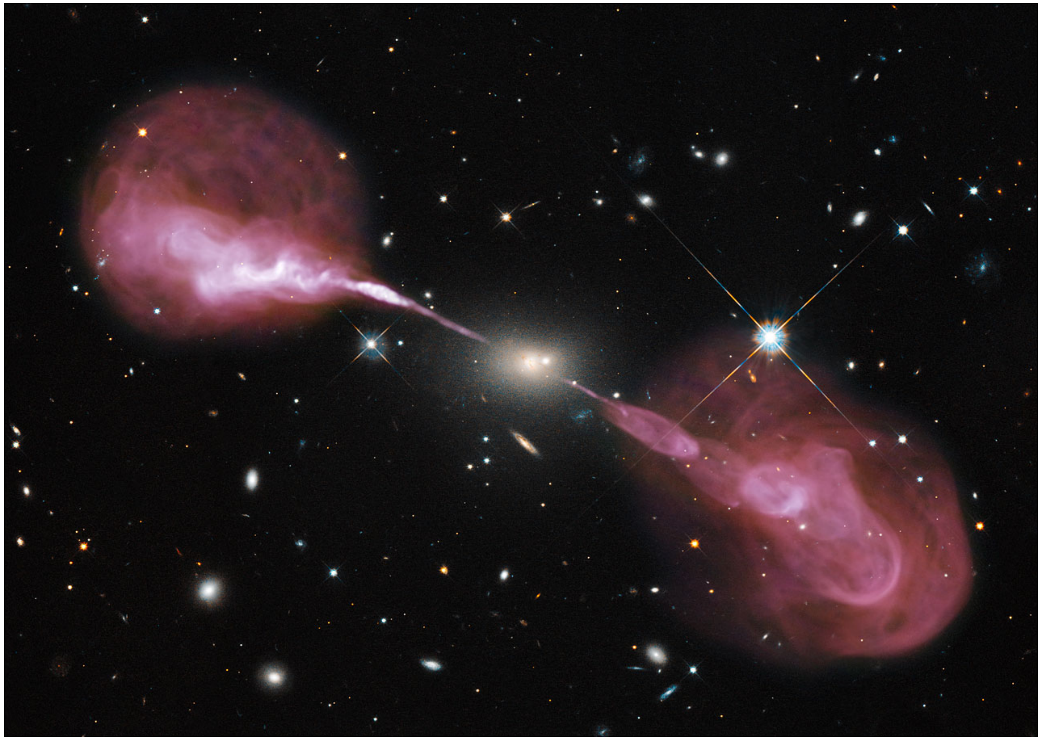
1. Convert to thermal energy in the flow and expand it (resisto-jets, arc-jets and magnetic mirrors)

2. Electrostatic acceleration (ionise the propellant, separate electrons and ions and apply electric fields independently)

3. Magneto-hydrodynamic acceleration (ionise the propellant, accelerate the neutral plasma using J x B)

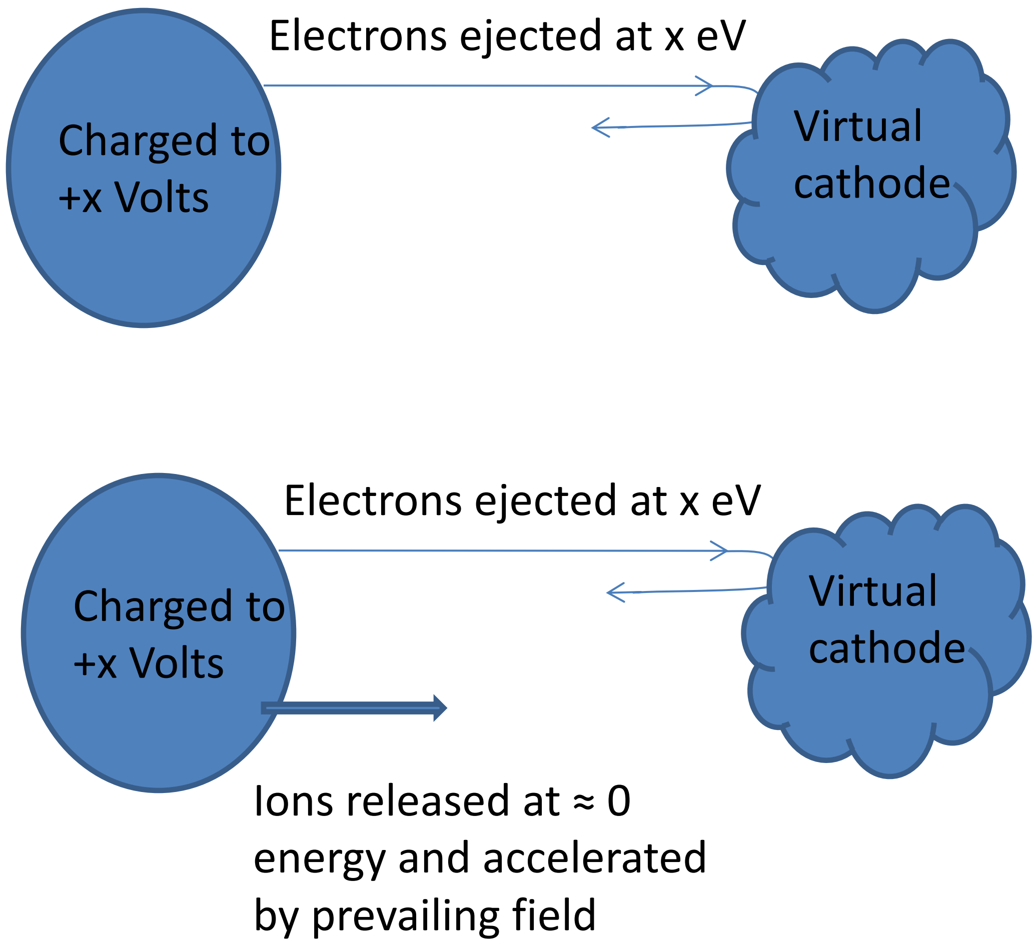
Within each of these categories many ingenious configurations have been devised, sometimes with a contribution from a little of each.

Is the Universe trying to say something?

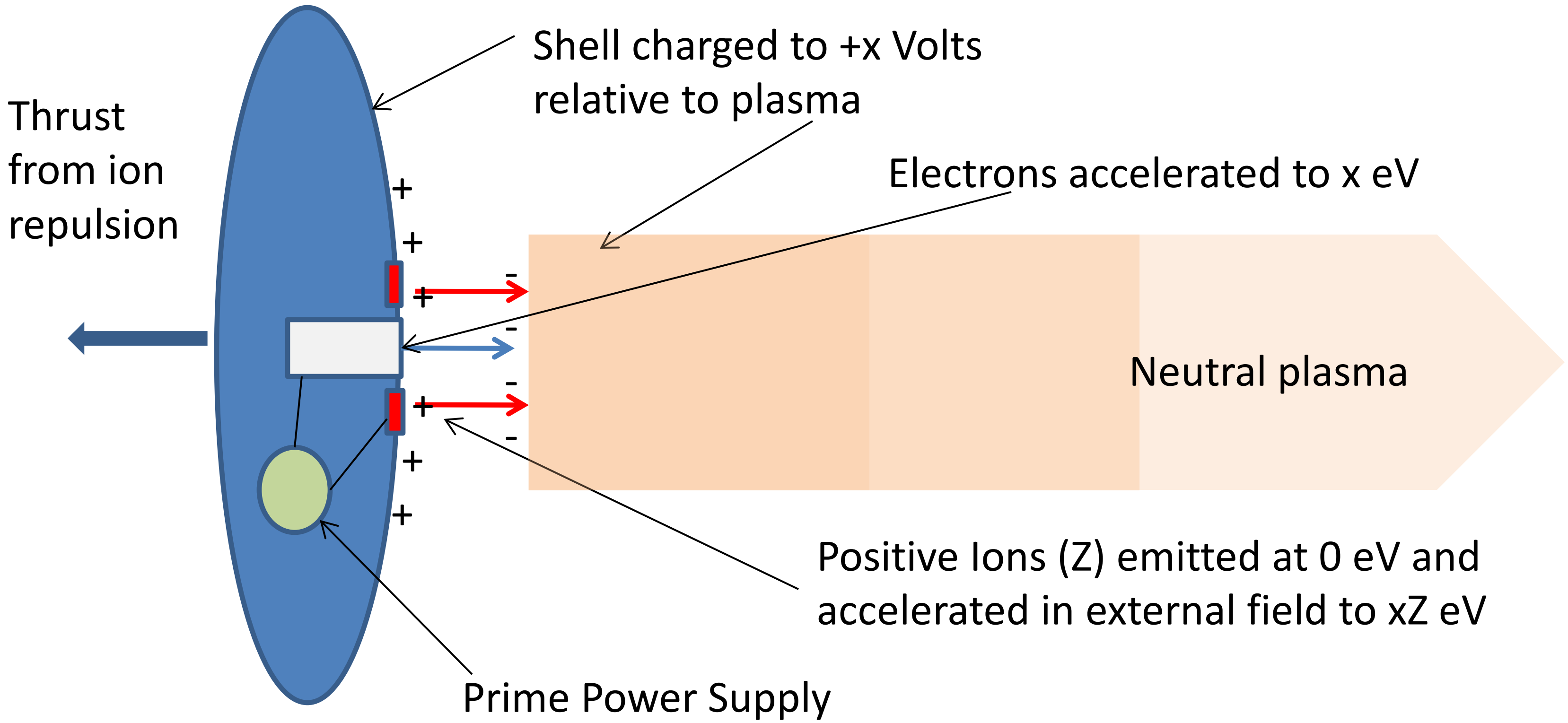


These jets are up to a million light years in length and have energy 25MeV with almost no divergence. How? – we don't know! But, it has to be electromagnetic acceleration.

A different electrostatic Thruster



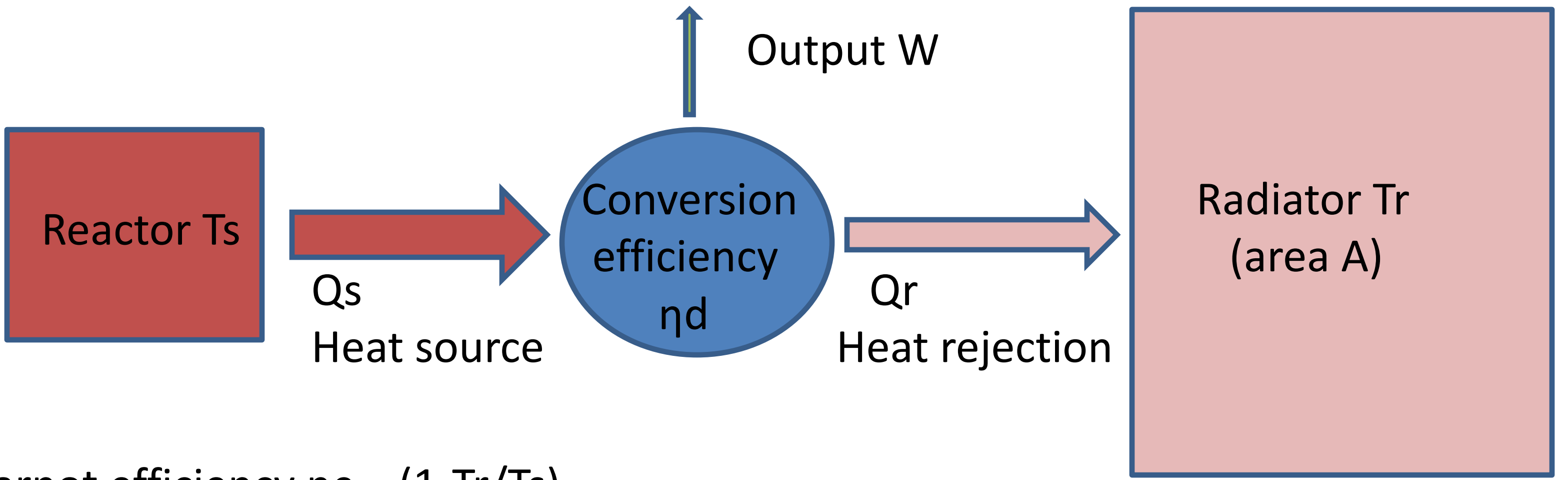
Variable Exhaust Velocity Electrostatic Engine concept



The Power Supply (1)

For missions to the outer Solar System and propulsion power in the tens of MW nuclear power is the only realistic option.

Currently nuclear energy has to pass through a thermal conversion cycle subject to the second law of thermodynamics.



Carnot efficiency $\eta c = (1 - Tr/Ts)$

$W = (Qs - Qr) = \eta c . \eta d . Qs$

The Power Supply (2)

The radiator is heavy and to minimise its area there is an optimum Carnot efficiency depending on the device efficiency:-

$$\eta_c = \frac{2}{5 + \sqrt{25 + 16\eta_d}}$$

ηd	ηc	ηd.ηc
1.0	.25	0.25
0.8	.235	0.188
0.6	.224	0.134
0.4	.215	0.086
0.2	.207	0.041
0	.2	0

Hence the power supply throws at least 80% to 85% of the energy it generates away as waste heat.

The Power Supply (3)

The conversion system is normally (but not necessarily) one of:-

1. thermo-electric
2. thermionic
3. thermo-dynamic

↓ Increasing device efficiency

For 10s MW of electrical power the reactor must deliver 100s MW thermal power and thermo-dynamic systems using alkali metal coolant and working fluids provide the lightest option, although for smaller power supplies thermionic could be promising.

Thus the power supply must operate hot to minimise the radiator area and generate a lot of power to waste.

An efficient non-thermal conversion of nuclear power to electricity is highly desirable.

The Power Supply (4)

Inertial Electrostatic Confinement Fusor
(mainly following G.H.Miley)

The Power Supply (5)

Characteristics (very preliminary & speculative)

reaction $^{7}Li + {}^{1}H \rightarrow 2\ {}^{4}He$ +17.4 MeV

(side channel (0.7%) 14 &17 MeV (γ)

cross section 6.5mb for 1 MeV protons

(threshold at 1.8MeV for ^{7}Be reaction)

1GW direct energy conversion 4.5MV x 230A (approx)

The Power Supply (6)

Problems –MANY!!

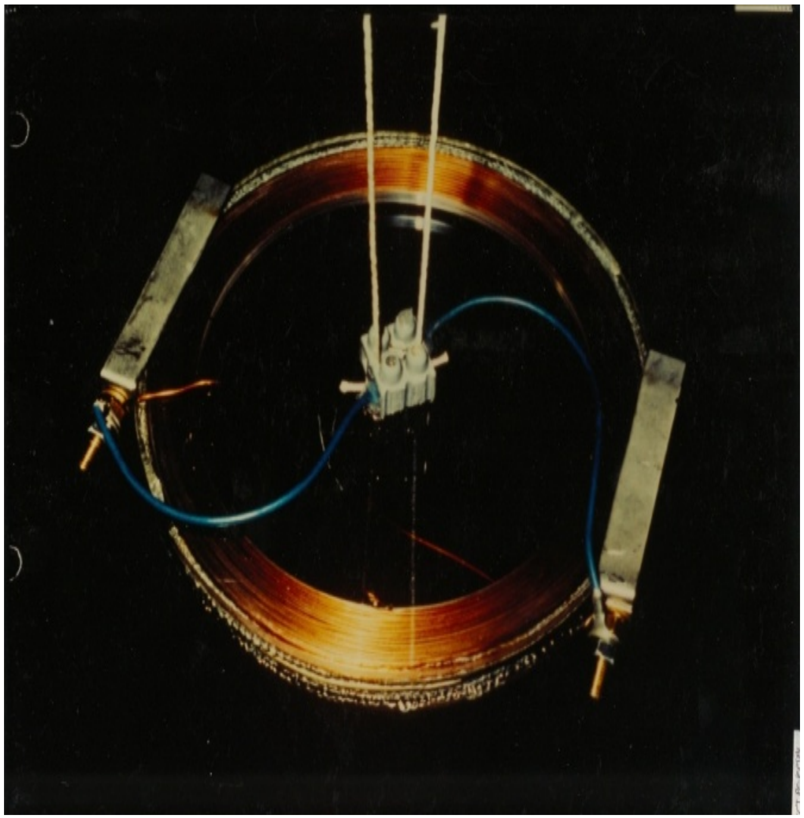
- Bremsstrahlung   155MW for 2keV electron temp
- shielding against 7MW of γ
- Getting the physics to work is the greatest problem!

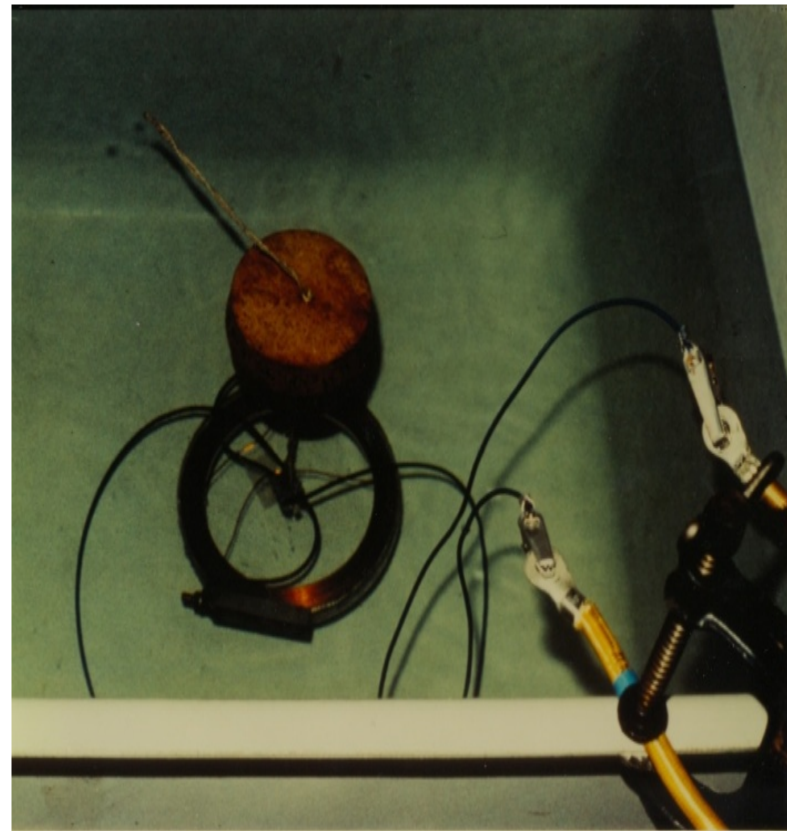
But the reward would be enormous, both for space and terrestrial power!

We have discussed electric propulsion in space

Could we use it to leave the Earth’s surface?

- Demonstration of MHD system 1978-1982

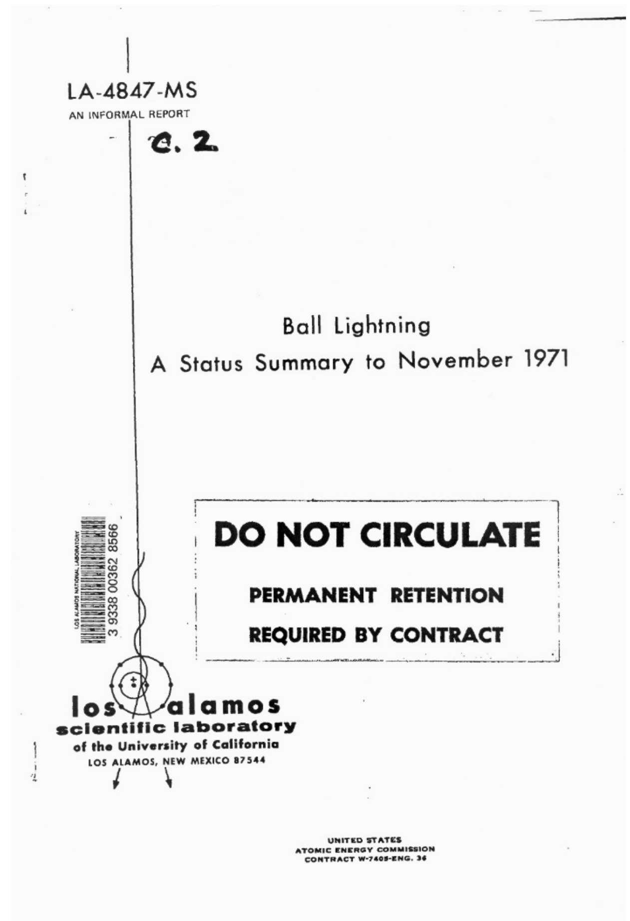




Proof of principle MHD test item suspended in salt water
A. Bond and A.R. Martin

- Problems with ionisation

LASER sustained discharge



LA-4847-MS
AN INFORMAL REPORT
C. 2

Ball Lightning
A Status Summary to November 1971

DO NOT CIRCULATE
PERMANENT RETENTION
REQUIRED BY CONTRACT

3 9338 00362 8566

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UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

Concept:-Atmospheric MHD Coupling (1)

- Why do it?

$$F = \rho A U . \Delta U$$

$$\dot{E} = \rho A U . \Delta U . \left(U + \frac{\Delta U}{2} \right) = F . \left(U + \frac{\Delta U}{2} \right)$$

- Trade A against ΔU at constant F for a given altitude and velocity

- Aerodynamic lift due to profile

Concept:-Atmospheric MHD Coupling (2)

- Thrust from $f = \vec{J} \times \vec{B}$
- Electron drift velocity $u_d = 13500.\left(\frac{E}{p}\right)^{\frac{1}{2}}$
- Recombination loss $R_p = \sigma_r \overline{C}_i n_i^2 Q$

Sub Systems

- Ionisation: non-thermal equilibrium
- Magnetic field: superconducting
- Electrodes: emitting (hollow cathode) & non-emitting
- Prime power supply (PPS) (vacuum & fuel system)
- Shielding (γ)-tungsten
- Power conditioning
- Heat rejection (boiling lithium)

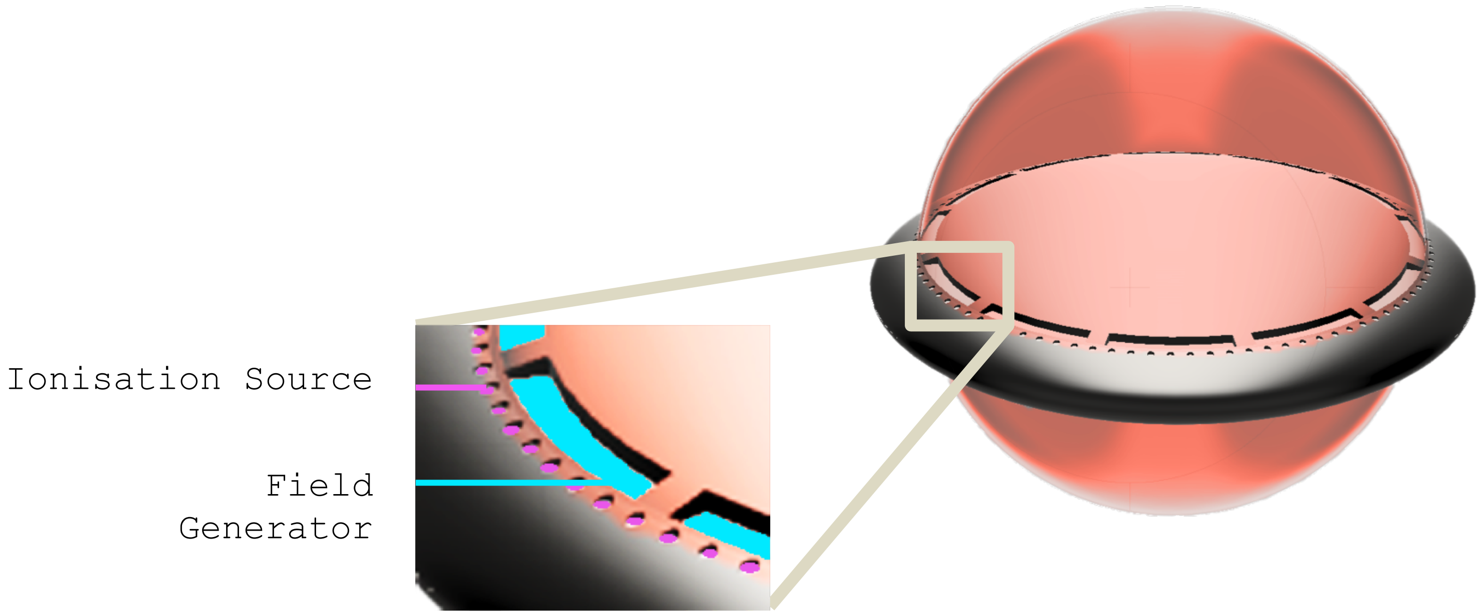
Overall System Analysis

Nominal Vehicle Specification

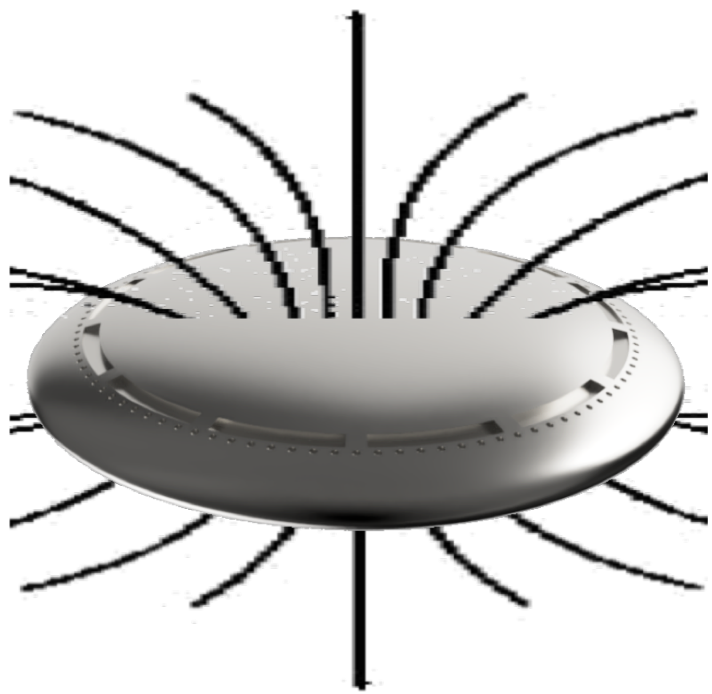
disc radius	3m
thickness ratio	0.2
mass	15t
nominal max power	1GW
nominal mag. field	0.5T
nominal electron density	$< 10^{20}/m^3$ (sea level)
ionisation power	7MW (optimised)
waste heat load	50MW

The Discus Vehicle

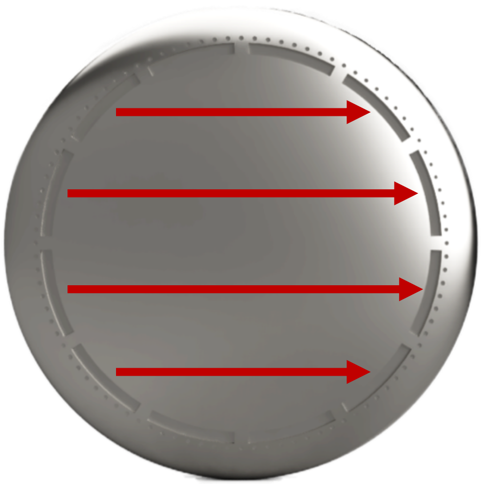
Ionisation region

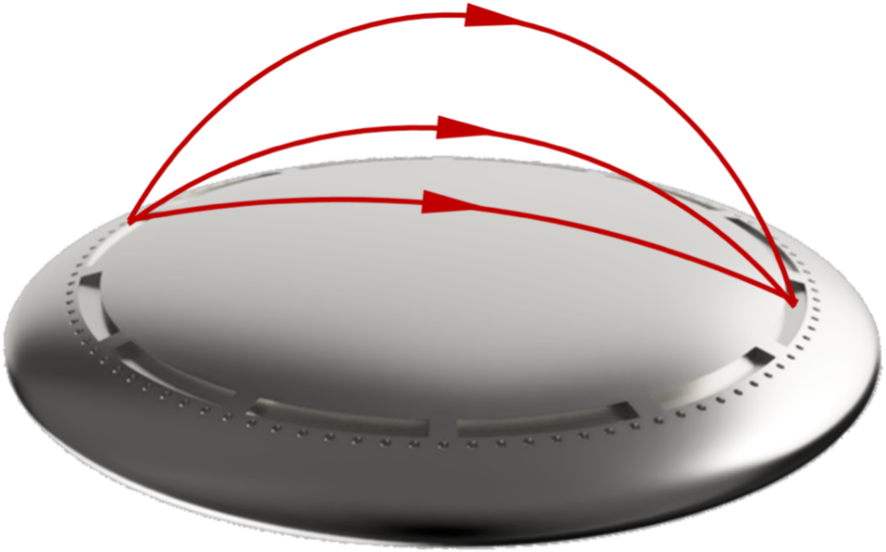


Magnetic Fields

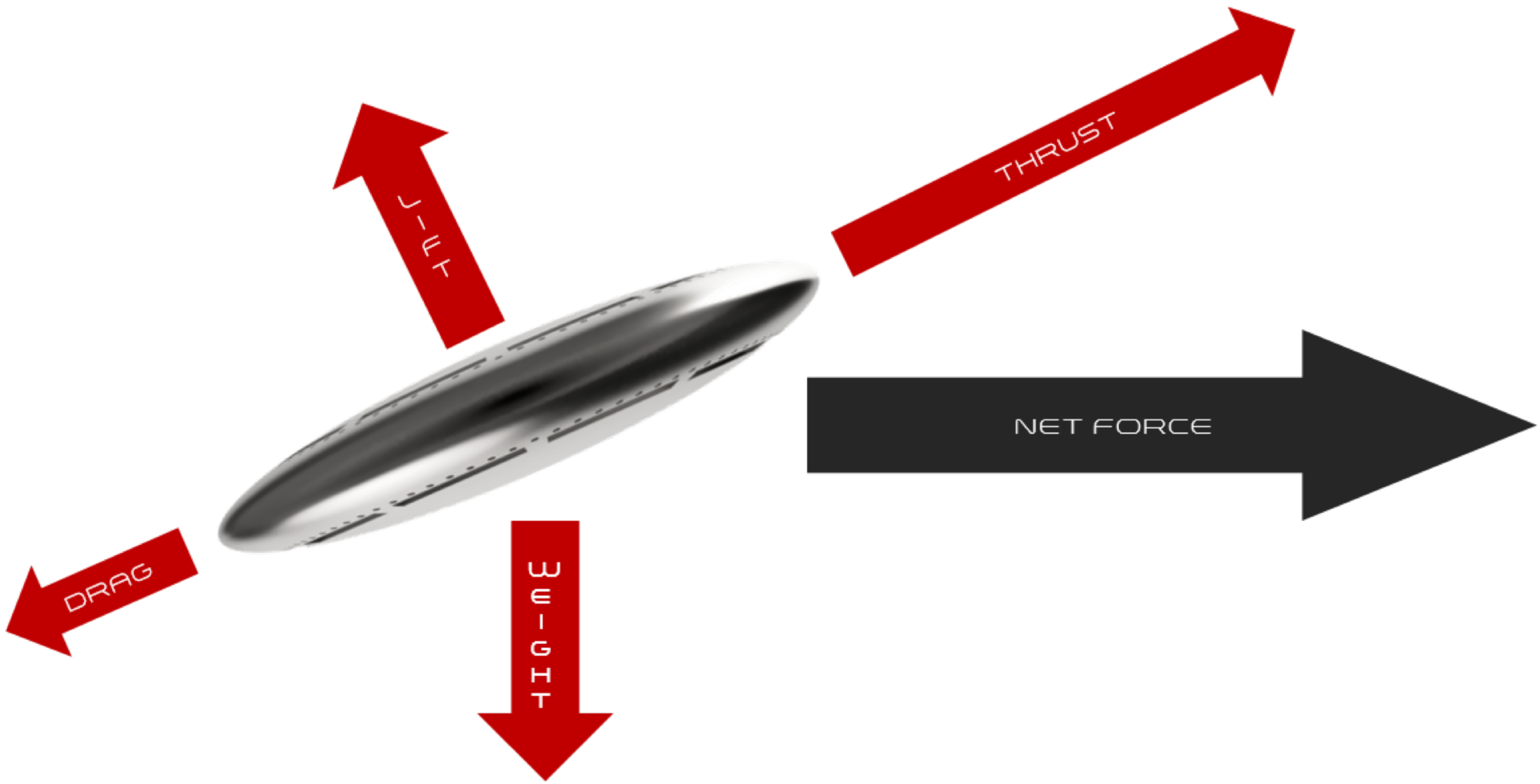


Currents

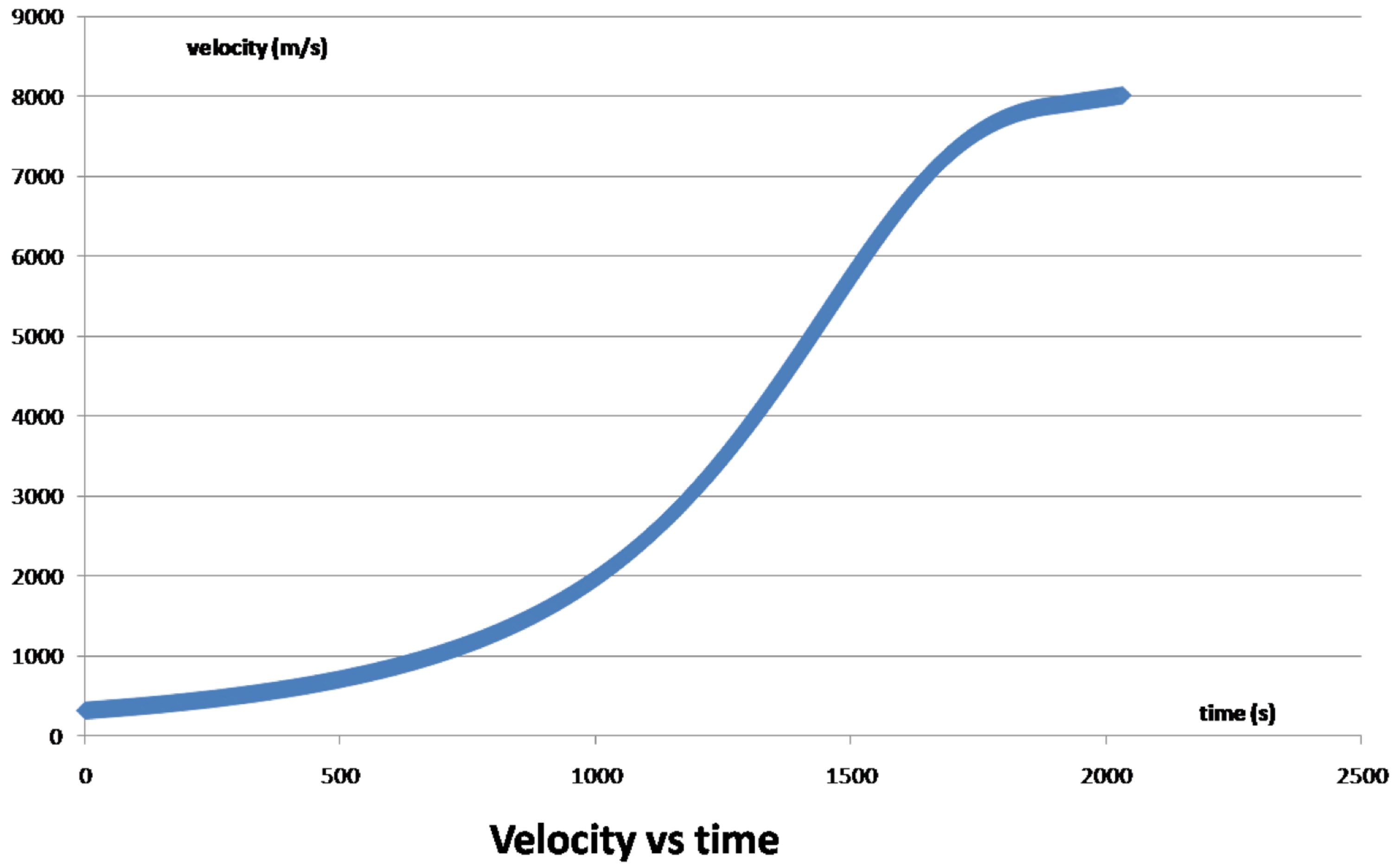




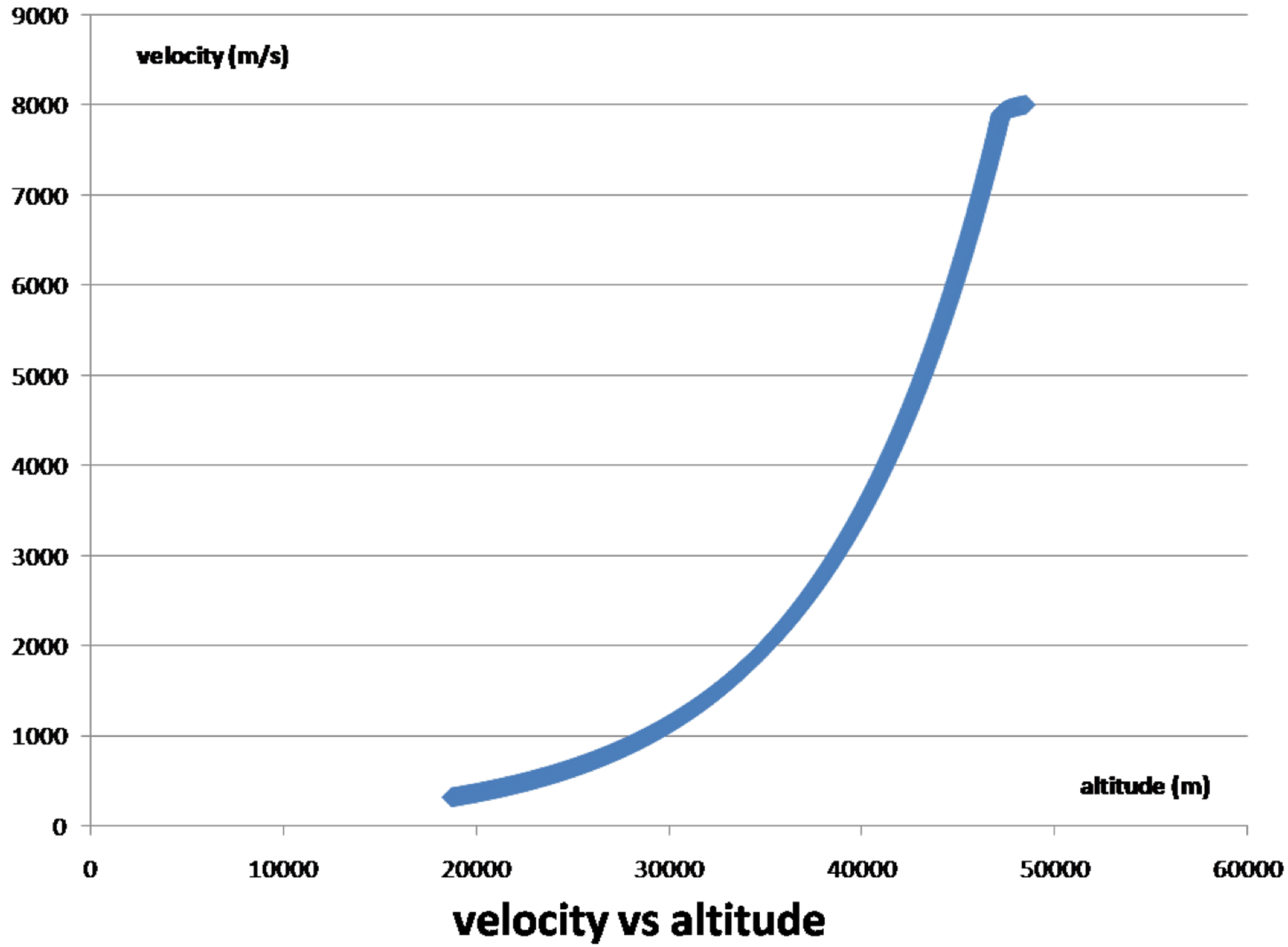
System of Forces



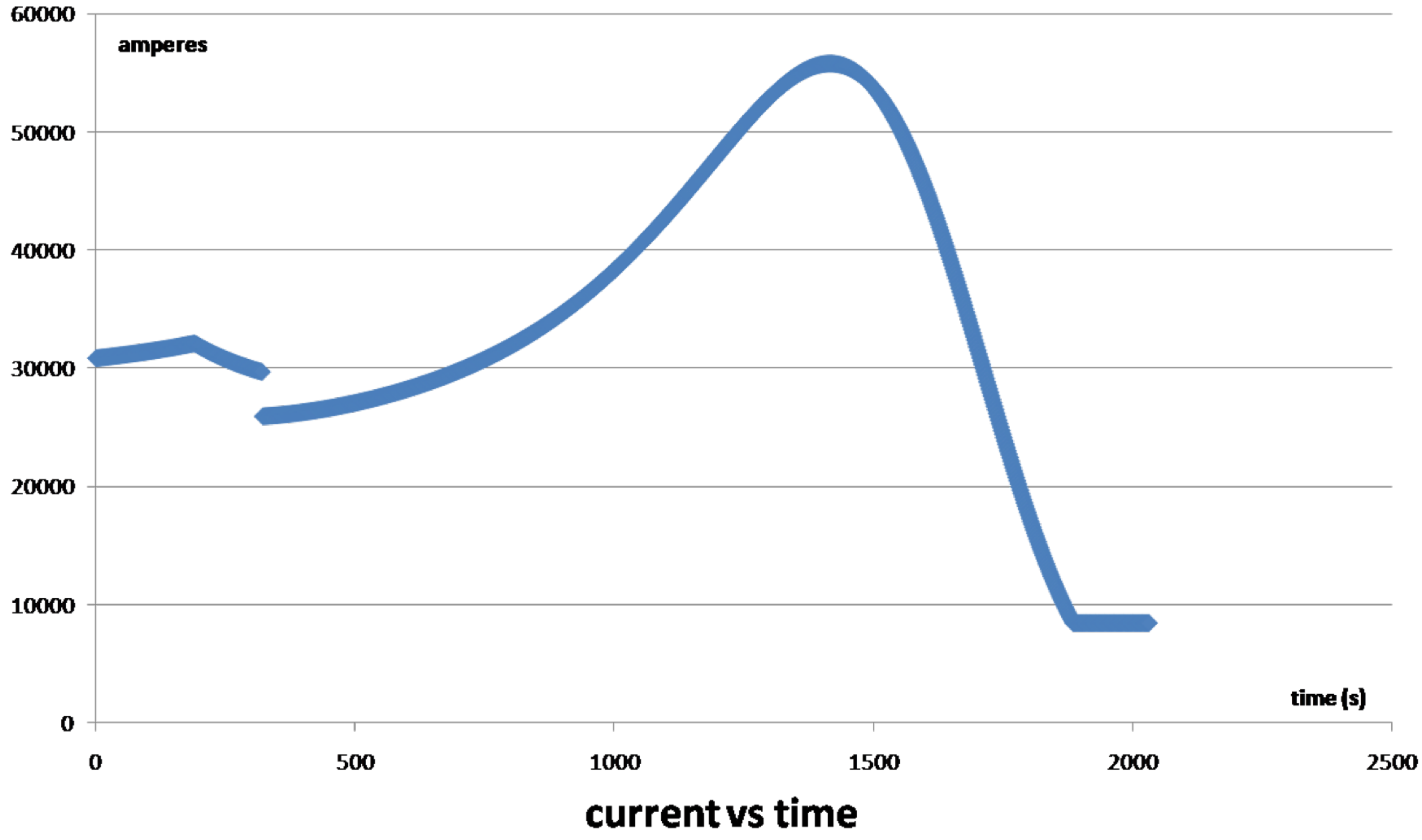
Trajectory Simulation (1)



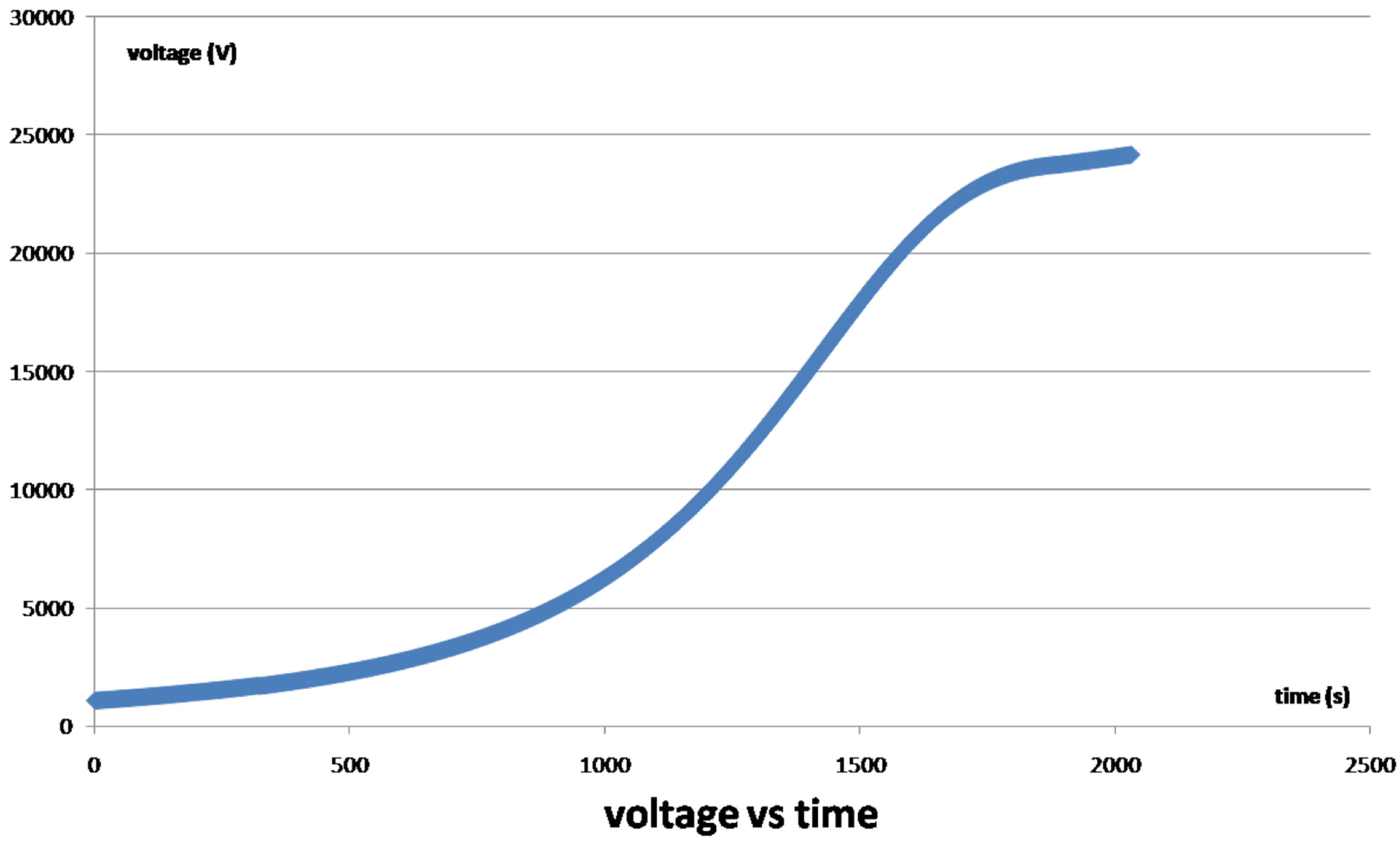
Trajectory Simulation (2)



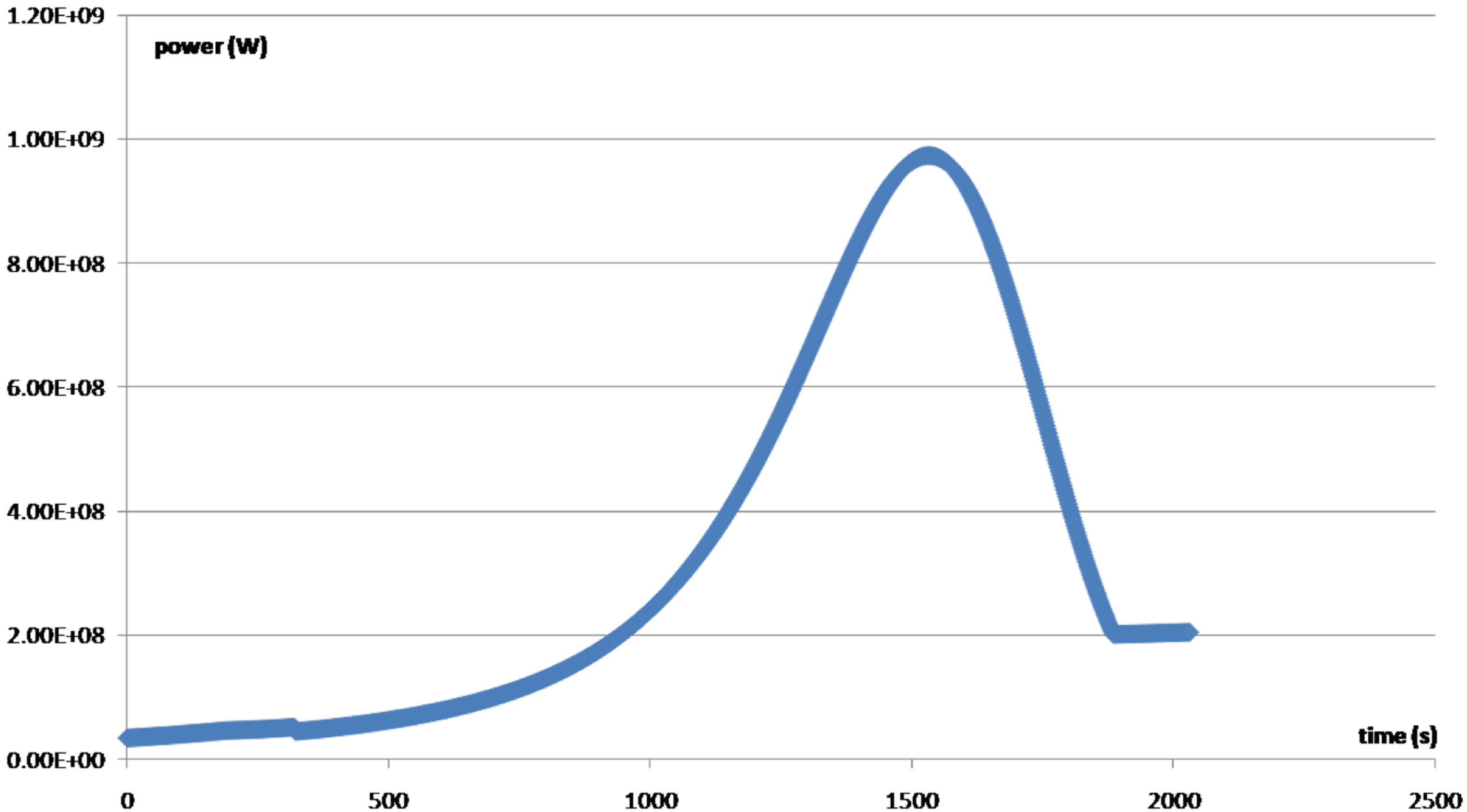
Trajectory Simulation (3)



Trajectory Simulation (4)



Trajectory Simulation (5)



total power vs time

Conclusions

Over the coming decades of this century space electric propulsion could be extended to tens of megawatts electrical power, or beyond, with developments in technology at hand. Vehicles could reach hundreds of tonnes in mass and the Solar System could be reduced to months of transfer time in size.

Development of a more efficient and convenient power supply is highly desirable or, indeed, essential. If efficient direct conversion of nuclear energy can be achieved electric propulsion could even be applied to atmospheric flight and the space transportation of science fiction would become reality