EmDrive Propulsion

Roger Shawyer SPR Ltd

Technical University Dresden
11th July 2018

1. Origins and early development
2. EmDrive theory and thruster design
3. Experimental programmes
4. Application to a manned Moon mission

EmDrive Origins – Nuclear Missiles

In 1970s the cold war was at its height.

The UK nuclear warhead programme Chevaline was undergoing guidance & propulsion problems.

In his 1974 Royal Institution lecture Professor Eric Laithwaite suggested that gyroscopes could provide a means of reactionless propulsion. He was scorned by the academic establishment.

Sperry Gyroscope were asked to investigate. I joined the team that was tasked with *"think the unthinkable".*

We concluded that a mechanical system could not provide such propulsion but an electromagnetic one might, but with very low thrust.

I returned to electromagnetic sensor research, for a variety of autonomous weapon systems, used as advanced minefields for land and sea deployment.

Chevaline Warhead. Imperial War Museum

EmDrive Origins – Military Communications Satellites

Whilst the official project had been shelved, I maintained interest in the Electromagnetic concept out of simple curiosity.

In the mid 1980s I was working for Marconi Space and Defence systems on the Skynet 4 programme.

The Skynet 4 processing channel, for which I was responsible, gave good protection from jamming.

However as was succinctly pointed out, nothing would protect the satellite from *"a couple of ounces of C4 and a bag of nails".* The Mine Warfare course at HMS Vernon now proved useful !

As the US president now concedes *"Space is a warfighting domain".* It always has been.

Continuous manoeuvring and stealth are required to survive in a warfighting domain.

I decided to design and test an experimental thruster in my garage.

Original Experimental EmDrive Thruster

EmDrive Development at SPR Ltd

After considerable part time effort I was confident a working thruster could be built. However the concept was rejected by my employers who were, by then, Matra Marconi Space, (now Airbus).

There had been heavy company commitment to the Arianne 5 programme and the French management insisted that *"no new propulsion concepts would be considered for at least a decade".*

In the UK, Project Greenglow was underway, (the UK version of the NASA BPP programme).

In 2001 I formed SPR Ltd to see how far I could take the concept.

Within 6 months we won a SMART award from the DTI, with technical oversight by MoD.

Financial support from DTI continued for 5 years and we produced a Demonstrator Engine.

In 2006 we obtained significant private investment enabling dynamic testing and the start of a superconducting thruster programme.

SPR Demonstration EmDrive Engine

SPR Superconducting Thruster

EmDrive Development in the US and China

Following the 2006 New Scientist article, NWPU in China started work on EmDrive

In April 2010 NWPU revealed that they had measured 720mN of thrust for 2.5kW input, using a magnetron.

In 2012 NWPU published their first peer reviewed paper

In 2008 we attended a meeting at the Pentagon. USAF, USMC, RAAF, NASA & DARPA attended. Chaired by Director NSSO.

An export licence and TAA were set up and a technology transfer to the US was agreed

July 2010 Boeing Flight Thruster contract was completed

NWPU Experimental Thruster

SPR Flight Thruster

2008 Aerodynamic Model of an EmDrive spaceplane

Early superconducting EmDrive research had included application studies.

A model spaceplane using air turbine propulsion was manufactured and aerodynamically tested in Gibralta

Displayed at IAC08 conference in Glasgow

Basic EmDrive Science - Radiation Pressure

Electromagnetic waves carry momentum, whether travelling in free space or inside a waveguide

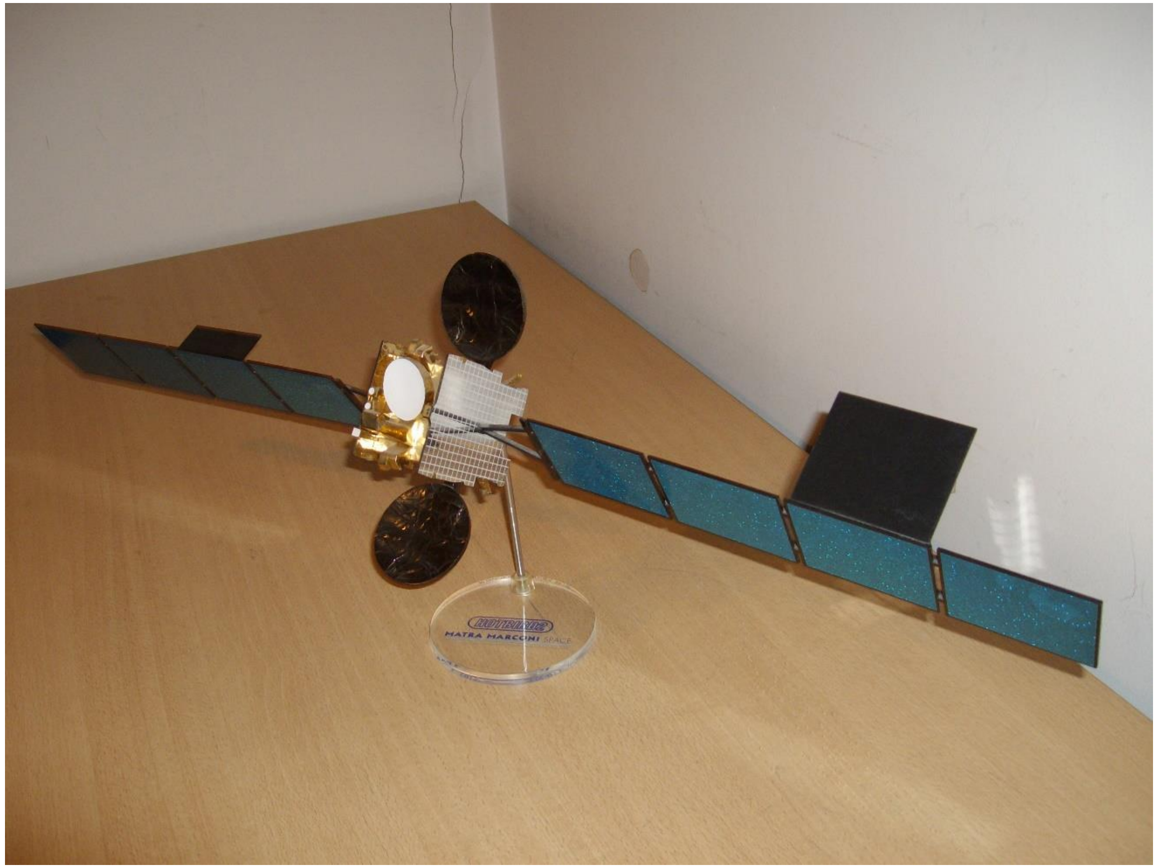
(Maxwell's equations)

When EM waves are reflected, this momentum is transferred to the reflecting surface and causes a force called radiation pressure

The force due to radiation pressure is

$$F = \frac{2P}{c}$$

This effect is used to assist roll and yaw control of satellites by using fixed flaps on the solar arrays



Radiation Pressure inside a waveguide

The force due to radiation pressure on the end plate of a waveguide is given by:

$F = \frac{2P}{c}\left(\frac{Vg}{c}\right)$ or $F = \frac{2P}{c}\left(\frac{\lambda o}{\lambda g}\right)$

Where λo is the free spacewavelength

λg is the group wavelength of the travelling wave inside the waveguide

The group wavelength in a circular waveguide is determined by the diameter:

$\lambda g = \frac{\lambda o}{\sqrt{1-\left(\frac{\lambda o}{K_{nm} D}\right)^2}}$ Where K_{nm} is determined by mode

When D =∞, $\lambda g = \lambda o$, Vg = c When D = cut-off diameter Dc, then $\lambda g = \infty$, Vg = 0 and wave propagation stops.

$Dc = \frac{\lambda o}{K_{nm}}$

Microwave Cavity

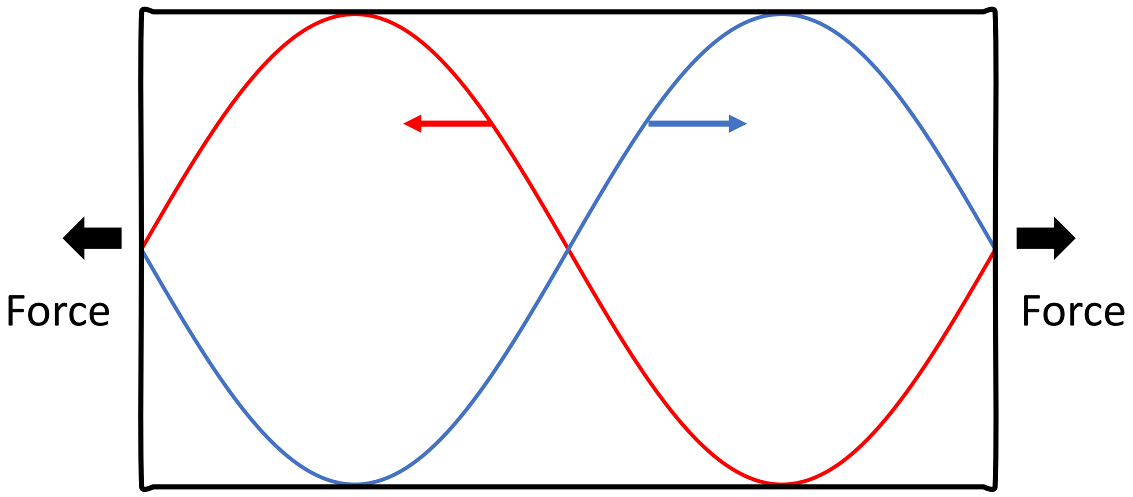
In a resonant microwave cavity multiple reflections of a travelling EM wave occur at the end plates

The number of reflections increase with the cavity Q

The total forces on the end plates increases with the number of reflections

$$F = \frac{2QP}{c}\left(\frac{Vg}{c}\right)$$

In the high Q superconducting cavities of particle accelerators the high radiation pressure on the end plates causes the sidewalls to stretch, and the length of the cavities to increase



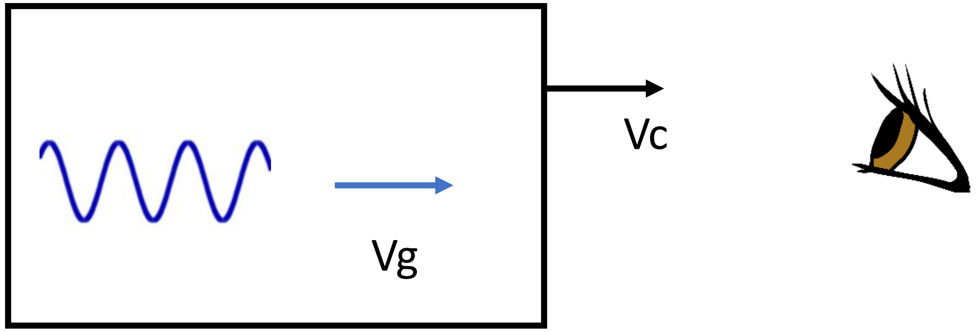
Independence of Velocities

The velocity of an EM wave inside the cavity Vg is independent of the velocity of the cavity Vc

An observer measures the velocity of the wave as Vg. Not Vg+Vc

(Einstein's theory of special relativity)

The wave and cavity form an **open** system allowing momentum to be transferred between wave and cavity



Forces in an EmDrive Cavity

For standing wave

$$F_1+F_2+F_w = 0$$

For travelling waves

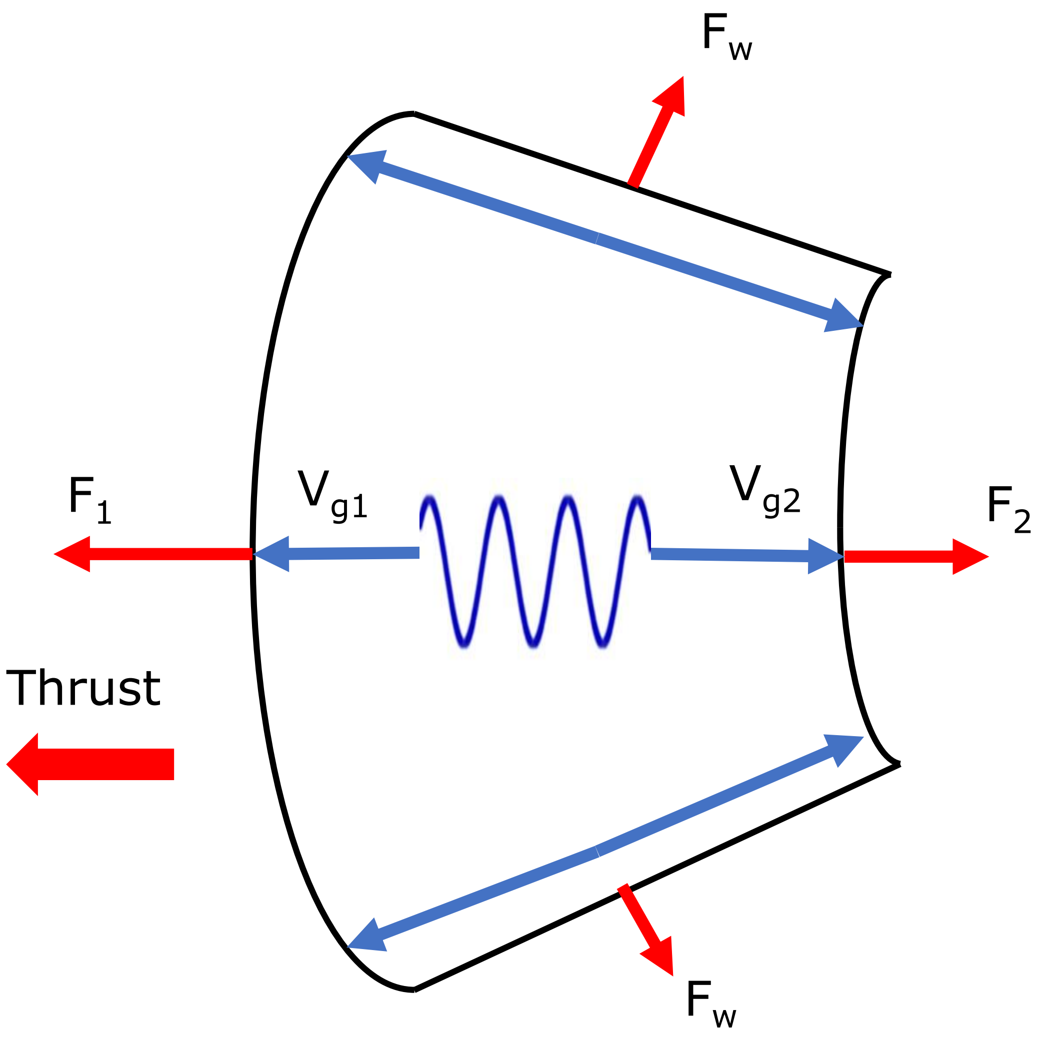
$$F_w = 0$$

$$V_{g1}>V_{g2}$$

$$F_1 > F_2$$

$$\text{Thrust} = F_1-F_2$$

Thrust T = $\dfrac{2QP}{c}\left(\dfrac{V_{g1}-V_{g2}}{c}\right)$

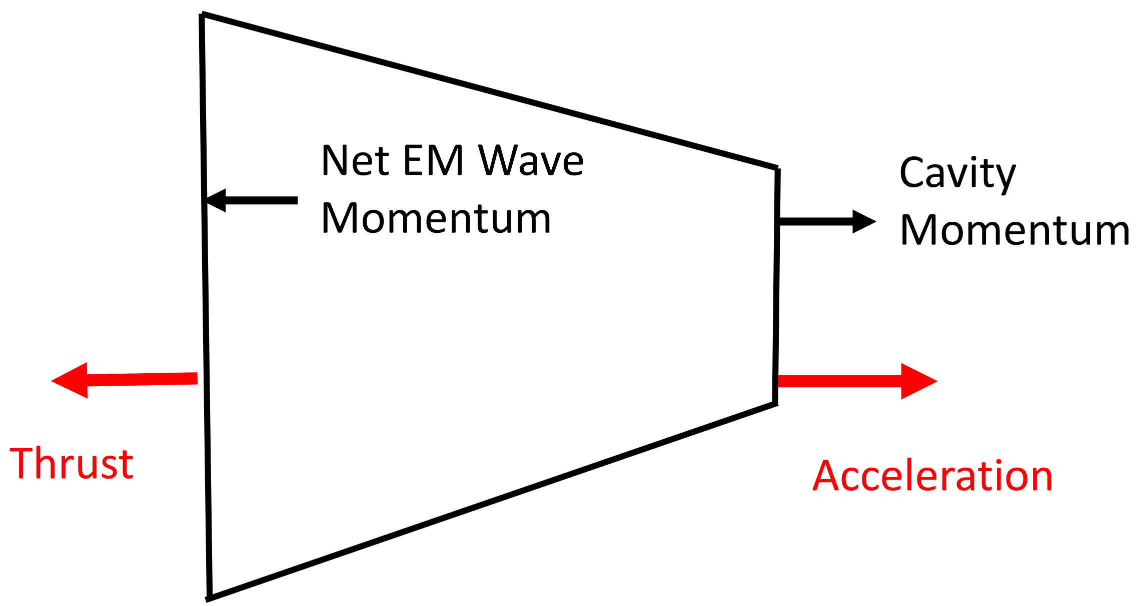


Conservation of Momentum

For a cavity in free space the thrust causes an acceleration in the opposite direction
(Newton's 3rd law)

The momentum lost by the EM wave is balanced by the momentum gained by the cavity

Momentum is conserved



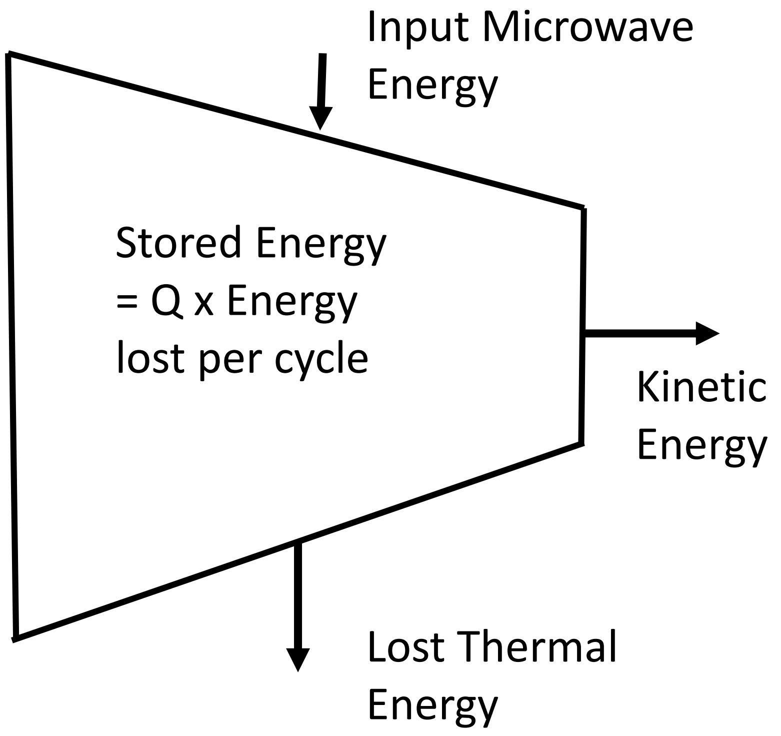
Conservation of Energy

Microwave input energy is stored in a resonant cavity for a short time

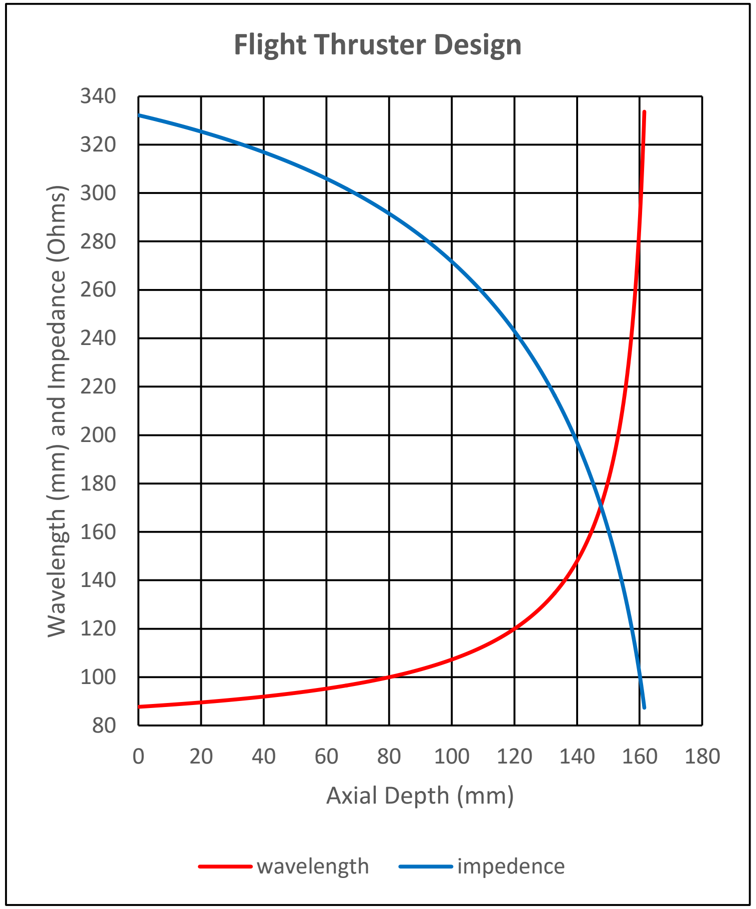
In a freely accelerating cavity with continuous input, some stored energy is converted into the kinetic energy of the cavity.
The rest of the input energy is lost as heat.

Note that as stored energy decreases, Q decreases and thus thrust decreases.

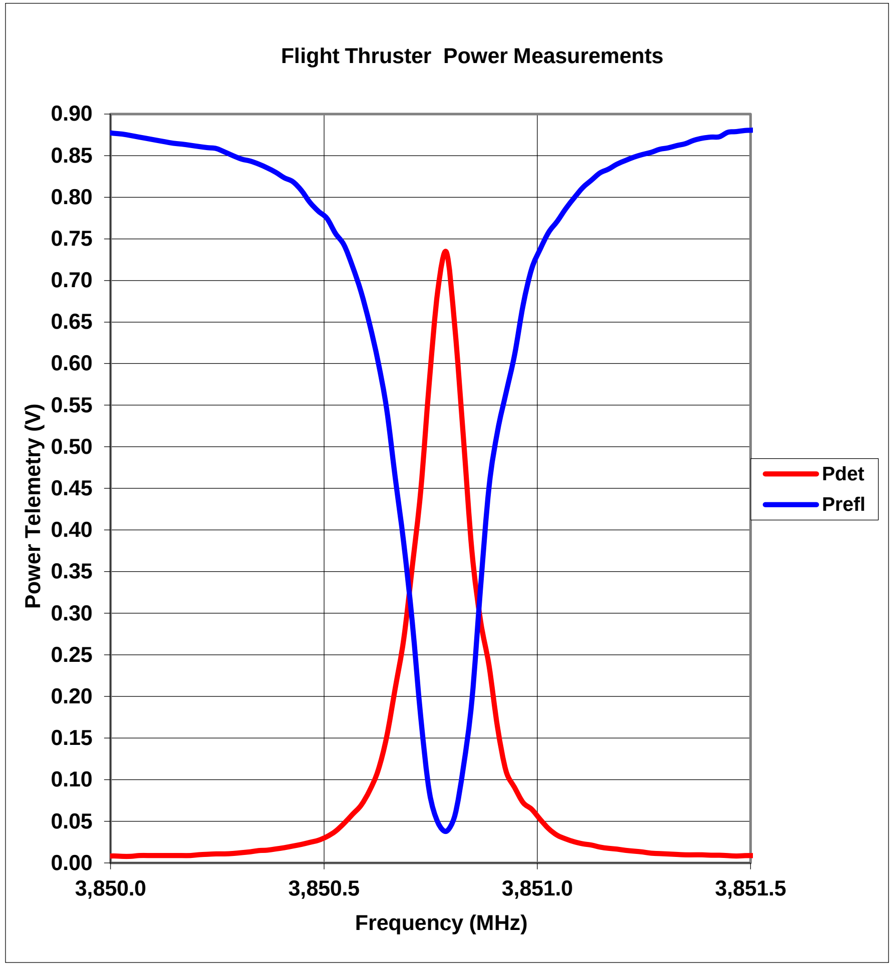
Energy is conserved



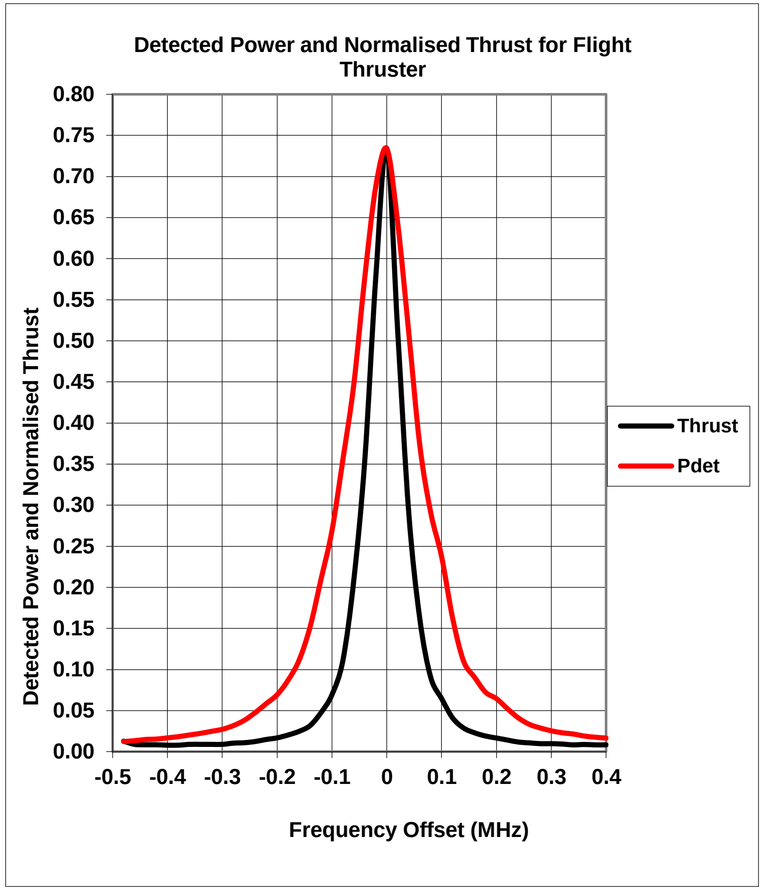
Input Circuit Impedance Matching



Input circuit impedance must be matched to the cavity impedance at the correct axial depth

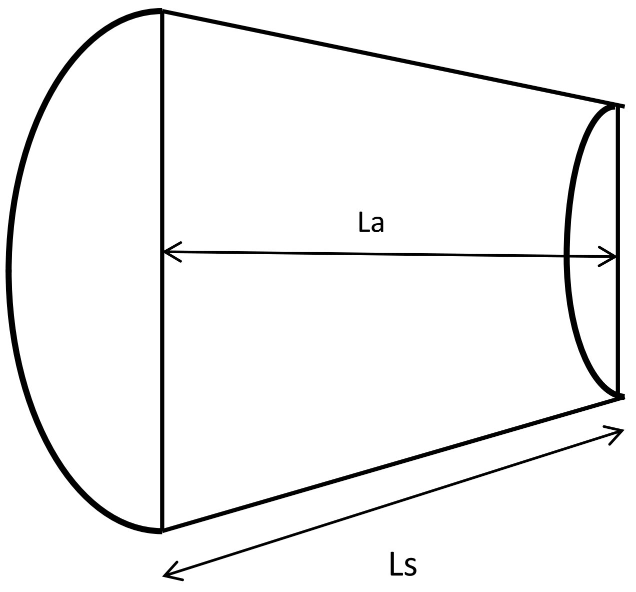


Correct match gives inverted but symmetric detected and reflected powers. Detected power is monitored with a probe inserted through cavity wall.



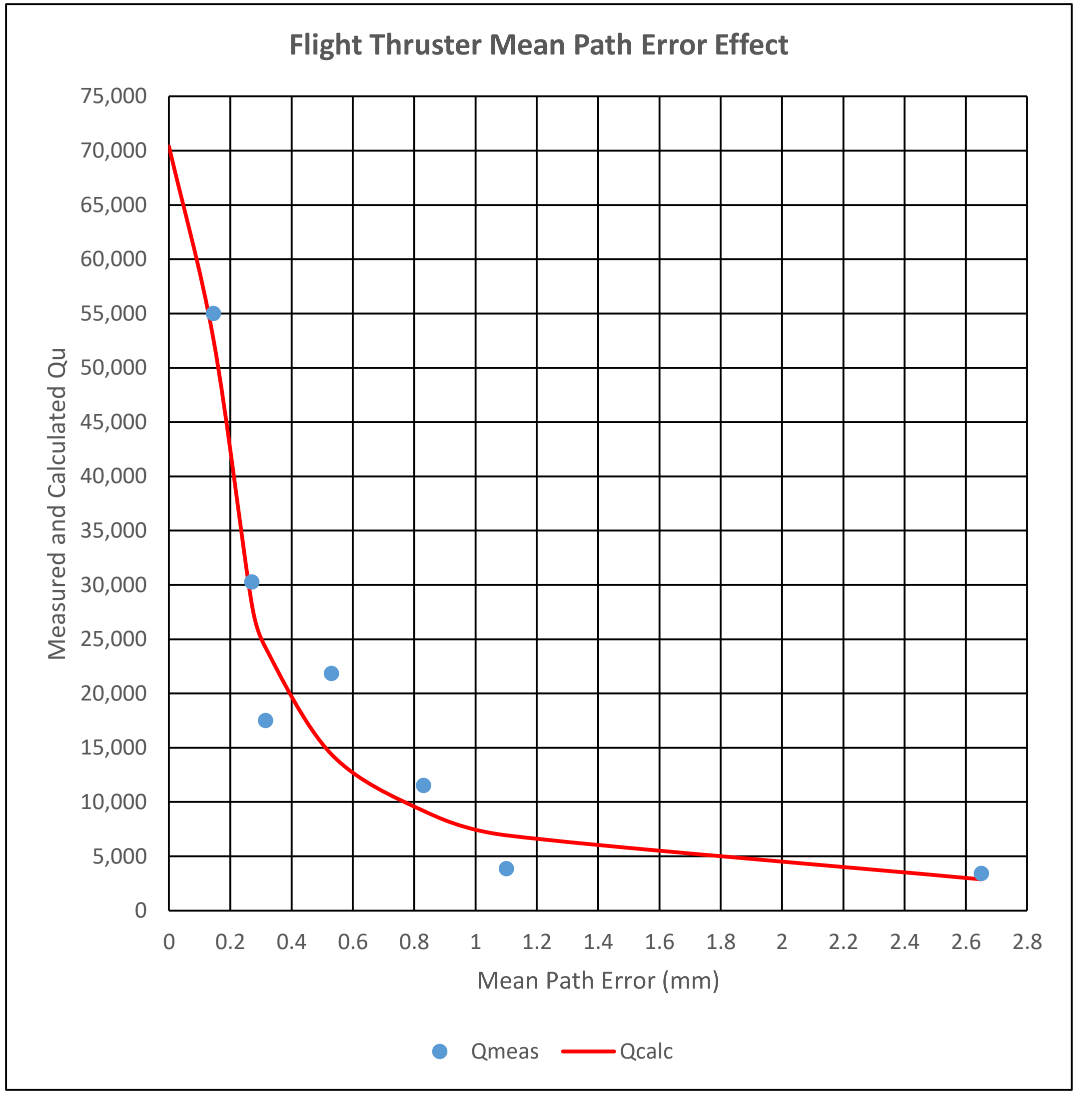
For correct match, Qu=2Ql Thus Thrust bandwidth is 0.5 Pdet bandwidth

Mean Path Error for Narrow Band Operation

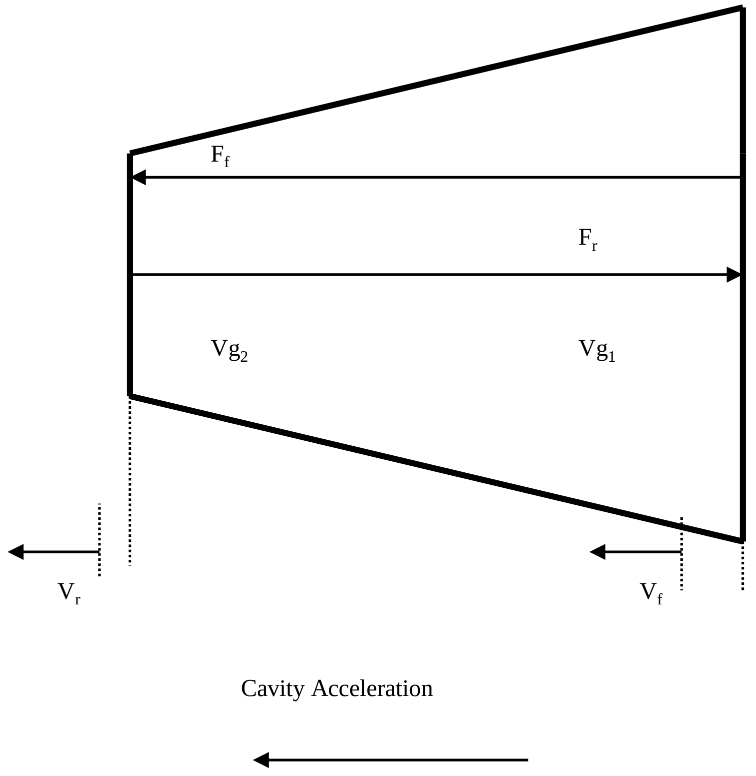


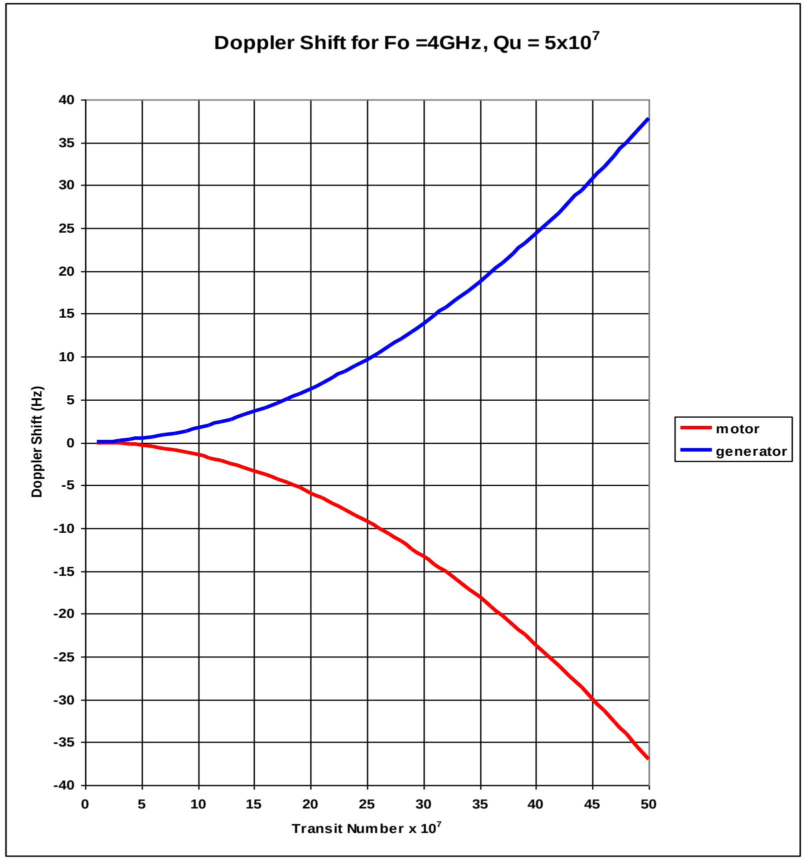
For flat end plates
Path length error = Ls-La
Total error =Q(Ls-La) leads to wavefront phase error and reduction of Q

End plates must be shaped and aligned to minimise mean path length error.



Acceleration Problem in a high Q cavity





Cavity acceleration produces unequal Doppler Shifts in F_f and F_r during each wavefront transit.

Doppler Mathematical model illustrates Doppler shift for both Motor and Generator modes.

EmDrive Development Generations

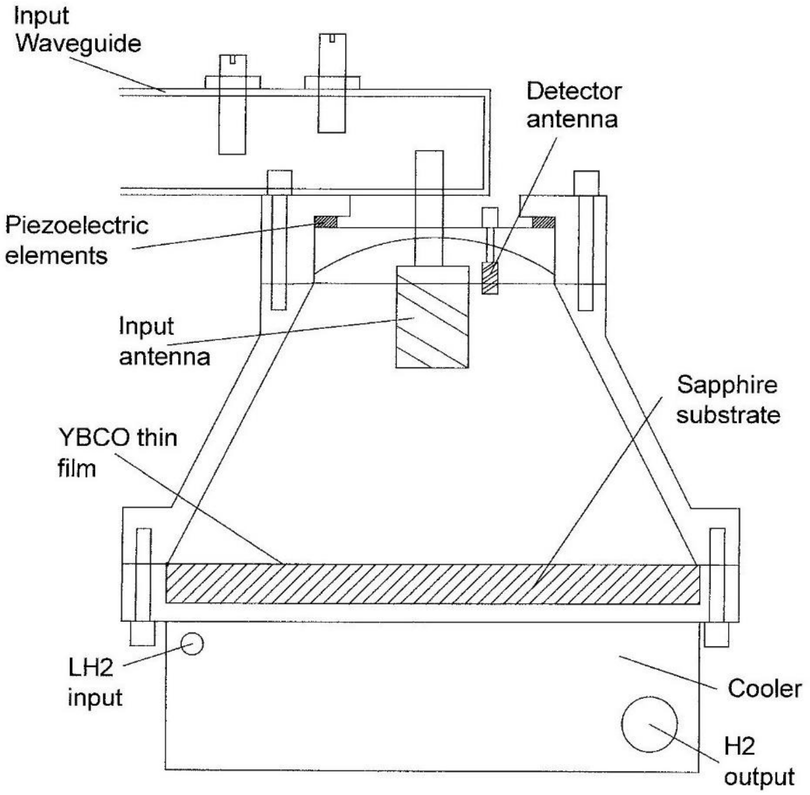
Thrust equation shows static thrust increases linearly with Q and Power.

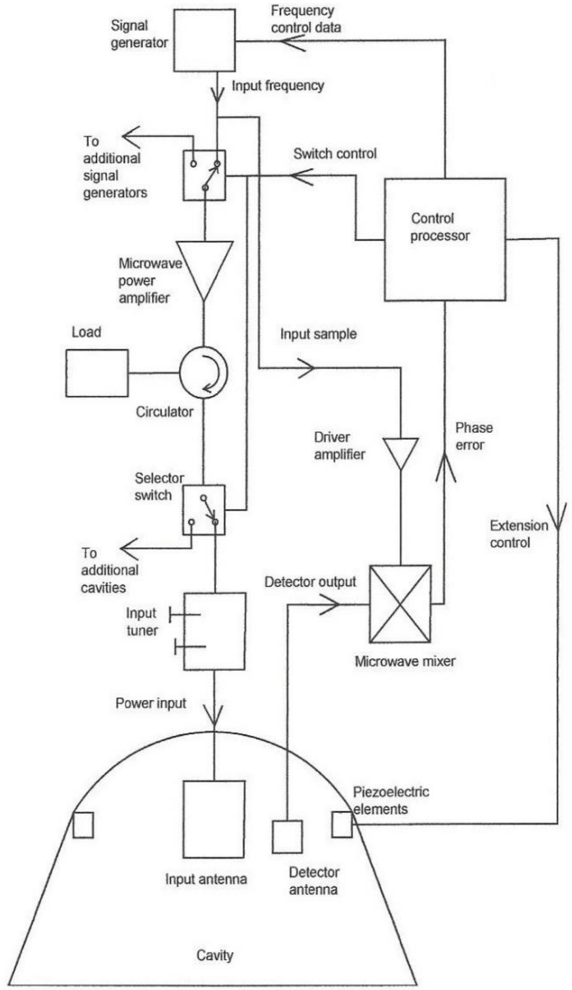
First Generation (1G). Uncooled microwave cavity. Low specific thrust.
In-orbit space applications.
$Q = 5x10^4$ Specific Thrust = 0.3N/kW

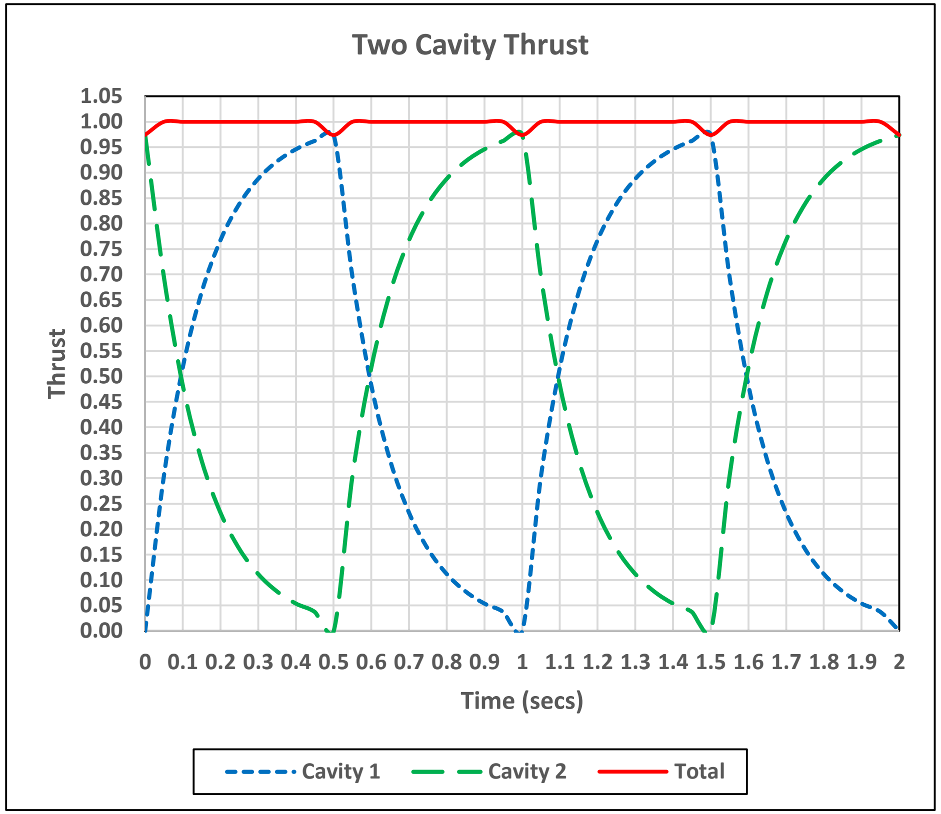
Second Generation (2G). Superconducting cavity cooled by liquid Hydrogen.
High Specific thrust. Low acceleration due to internal Doppler Shifts.
Marine applications.
$Q = 1.1x10^8$ Specific Thrust = 470N/kW Acceleration = 0.05 m/s^2

Third Generation (3G). Superconducting cavity cooled by liquid Hydrogen.
Very high specific thrust (high Q design). Doppler shift compensation.
Acceleration limited by conservation of Energy.
Aerospace applications
$Q = 7.7x10^8$ Specific Thrust =3,900N/kW Acceleration = 0.1 m/s^2

3G Thruster (Patent GB2537119)

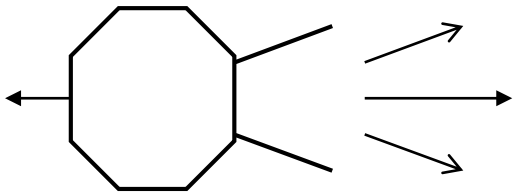




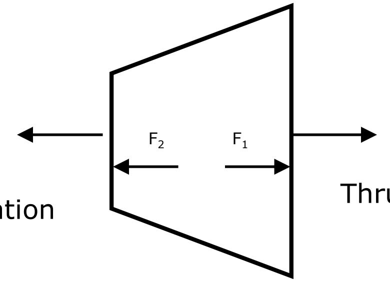


EmDrive is not a challenge for classic physics

Conventional Rocket



EmDrive Thruster



EmDrive is not a reactionless thruster, it is simply a new class of electrical machine

Classic Physics can answer all questions about EmDrive

How is Momentum Conserved? EmDrive obeys Newton's Laws

How is force produced? Radiation Pressure. Maxwell.

Why are the end plate forces different? Different group velocities due to different diameters. Cullen 1952

How is the force multiplied? EmDrive is a Resonant cavity with a multiplication factor Q. Bailey 1955

Why is EmDrive an Open System? Einstein's theory of Special Relativity

Why are there no side wall forces? Thrust due to travelling waves not standing waves.

How is energy conserved? EmDrive is an electrical machine.

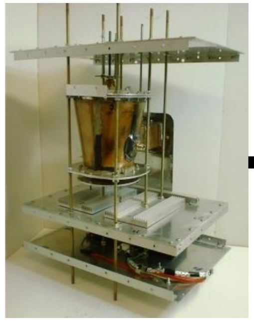
What limits thrust in high Q thrusters? Internal Doppler shift and Conservation of Energy.

How is thrust calculated? Thrust equation. Verified by a number of independent experimenters.

How is thrust measured? The thruster must be allowed to accelerate, otherwise Newton's Laws ensure a reaction force totally opposes the thrust. There must be some static load on the thruster otherwise all input energy becomes kinetic energy, stored energy falls to zero, Q falls to zero and thrust is zero.

UK Experimental Programme

2003



Experimental Thruster

2.45 GHz

$Q=5.9x10^3$

T=19mN/kW

Magnetron

2006

Demonstrator Engine

2.45 GHz

$Q=4.5x10^4$

T=243mN/kW

Magnetron

2010

Flight Thruster 3.8 GHz

$Q=5.8x10^4$

T=326mN/kW

2008

Experimental Superconducting Thruster 3.8 GHz

$Q=6.8x10^6$ (liquid nitrogen)

Predicted T=36N/kW

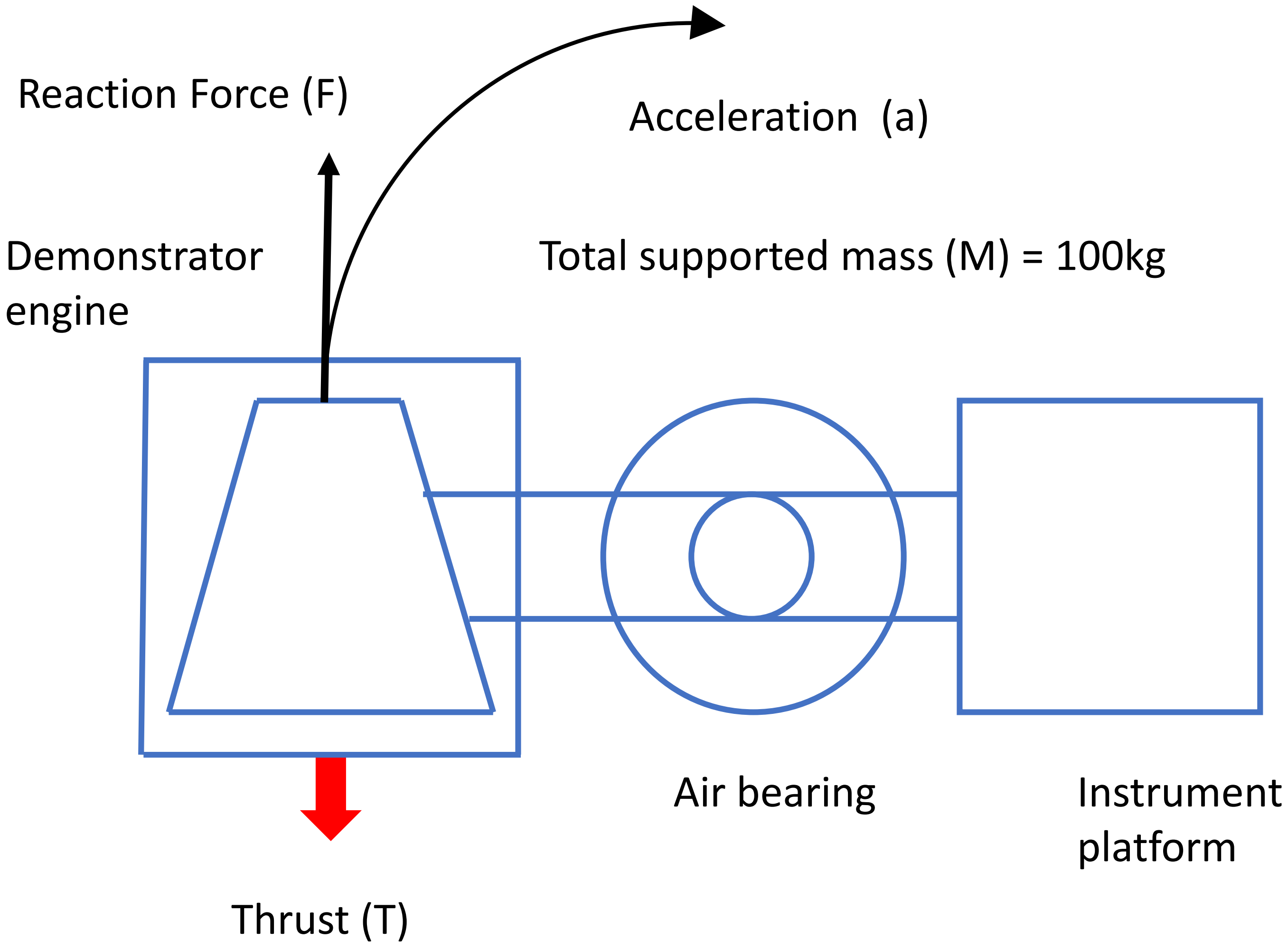
Both Flight and superconducting thrusters used narrow band inputs, requiring low manufacturing tolerances

Rotary Air Bearing Test Rig

Newton's Laws

3rd Law   F = -T

2nd Law   F = Ma



Dynamic Tests (2007)

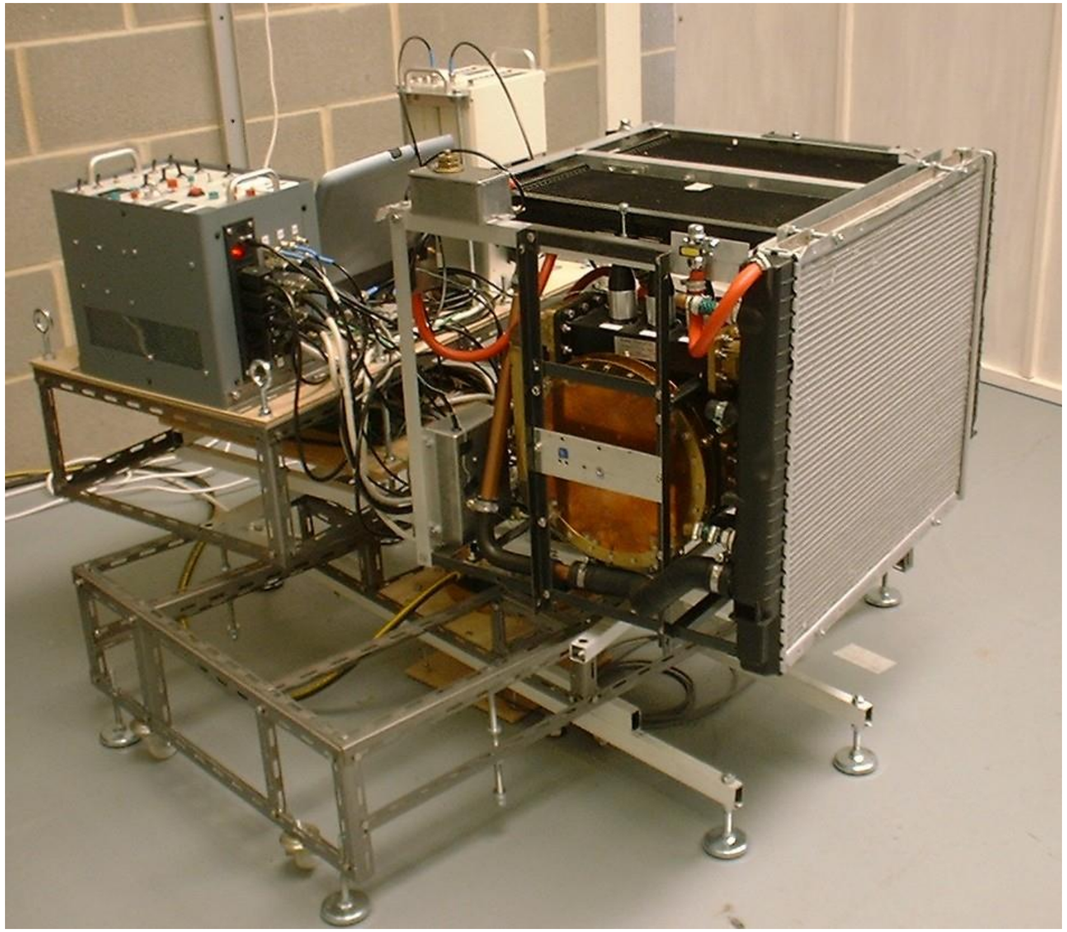
Acceleration of 100kg beam supported on air bearing to 2 cm/s

Direction of acceleration confirms that EmDrive obeys Newton's Laws

Acceleration only starts as magnetron frequency locks to resonant frequency. Magnetron provides wide band source and thus compensates for manufacturing tolerances.

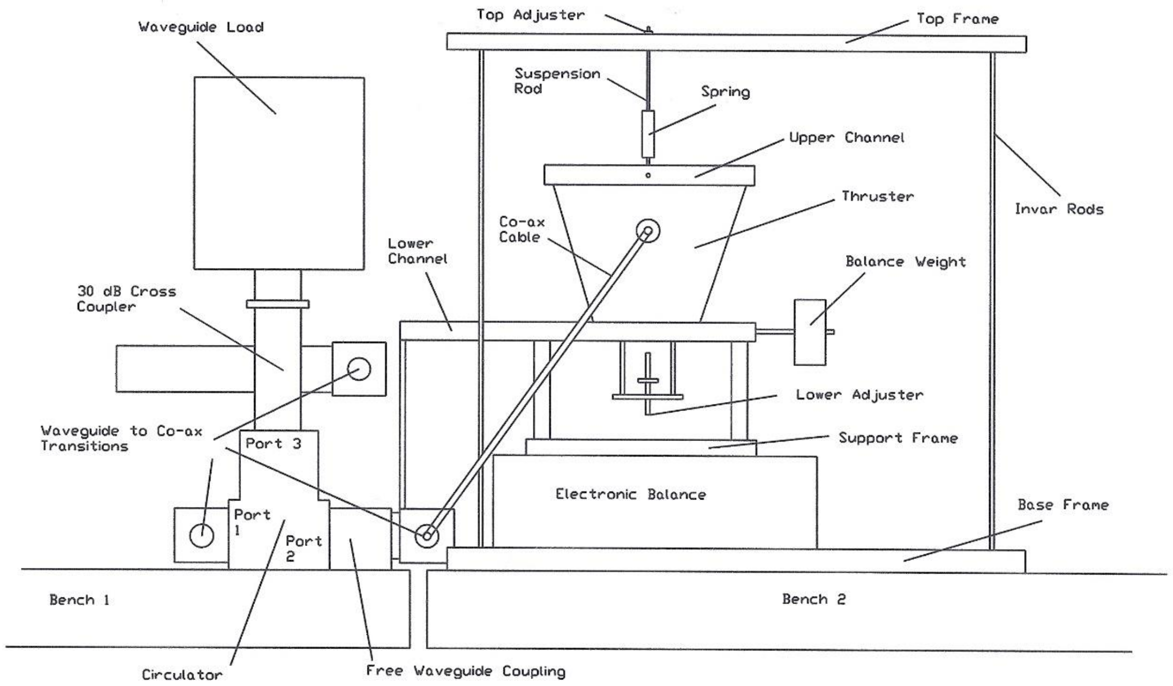
Programme included acceleration and deceleration runs in both directions

Calibration to determine friction torque carried out prior to each run. This provided the required static load to maintain thrust during acceleration.

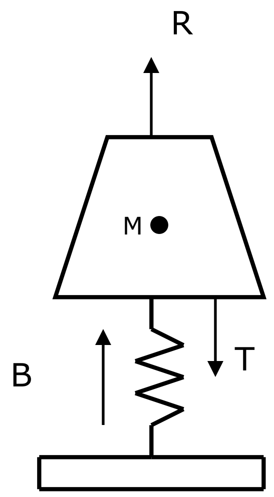


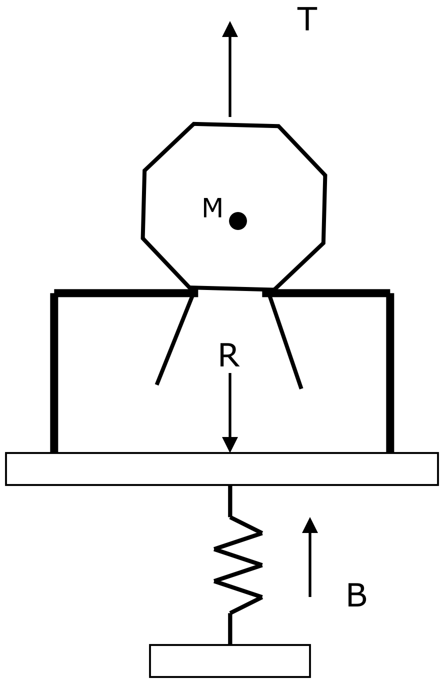
Static Vertical Test Rig

Capable of measuring Thrust or Reaction Force



EmDrive on simple Balance





Reaction Force = R

Thrust = T

In steady state T + R = 0

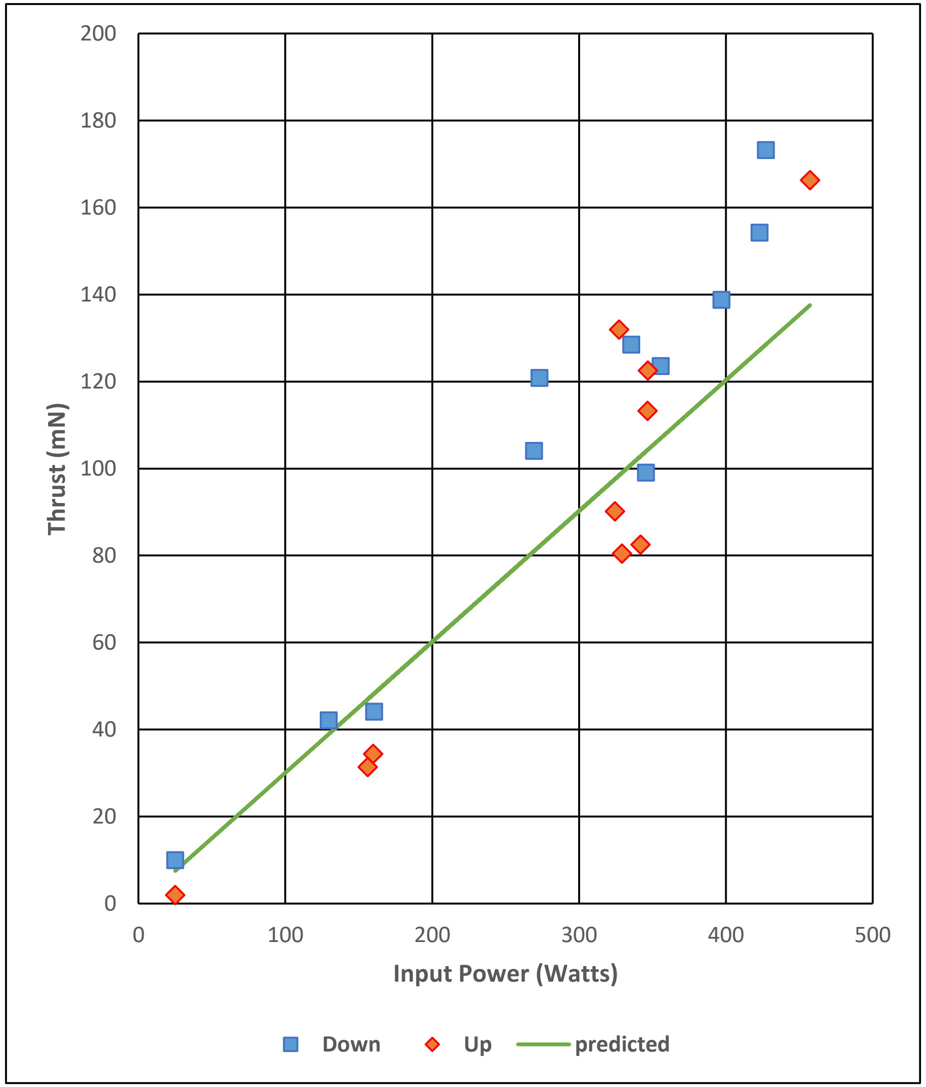
Then Balance force B = Mg

Analogy with conventional rocket on a balance, where reaction cancels thrust

Balance force B = Mg

2010 EmDrive Flight Thruster Test Results

- Flight Thruster data from 21 test runs of up to 90 seconds duration.
- Thrust vector up or down as shown
- Input power from 25W to 457W
- Measured mean specific thrust = 326mN/kW
- Predicted specific thrust = 301mN/kW
- Detailed test report delivered to Boeing
- Flight thruster required precision manufacture, careful input tuning and accurate end plate alignment, due to narrow band input.



Thermal Confirmation of Design Factor

The basic EmDrive Thrust equation is:

$$T = \frac{2QPD_f}{c}$$

Where the Design Factor $D_f = \left(\frac{V_{g1} - V_{g2}}{c}\right)$

D_f was used to predict the ratio of temperatures at each end plate of the Flight Thruster. This ratio was calculated to be 0.66.

The mean end plate temperature ratio for the Flight Thruster tests was determined to be 0.69 with a standard deviation of 0.03

This result gave an experimental, thermal confirmation of the Design Factor.

Torsion Balance Response

The results from a mathematical model of a simple un-damped torsion balance carrying an EmDrive thruster is shown.

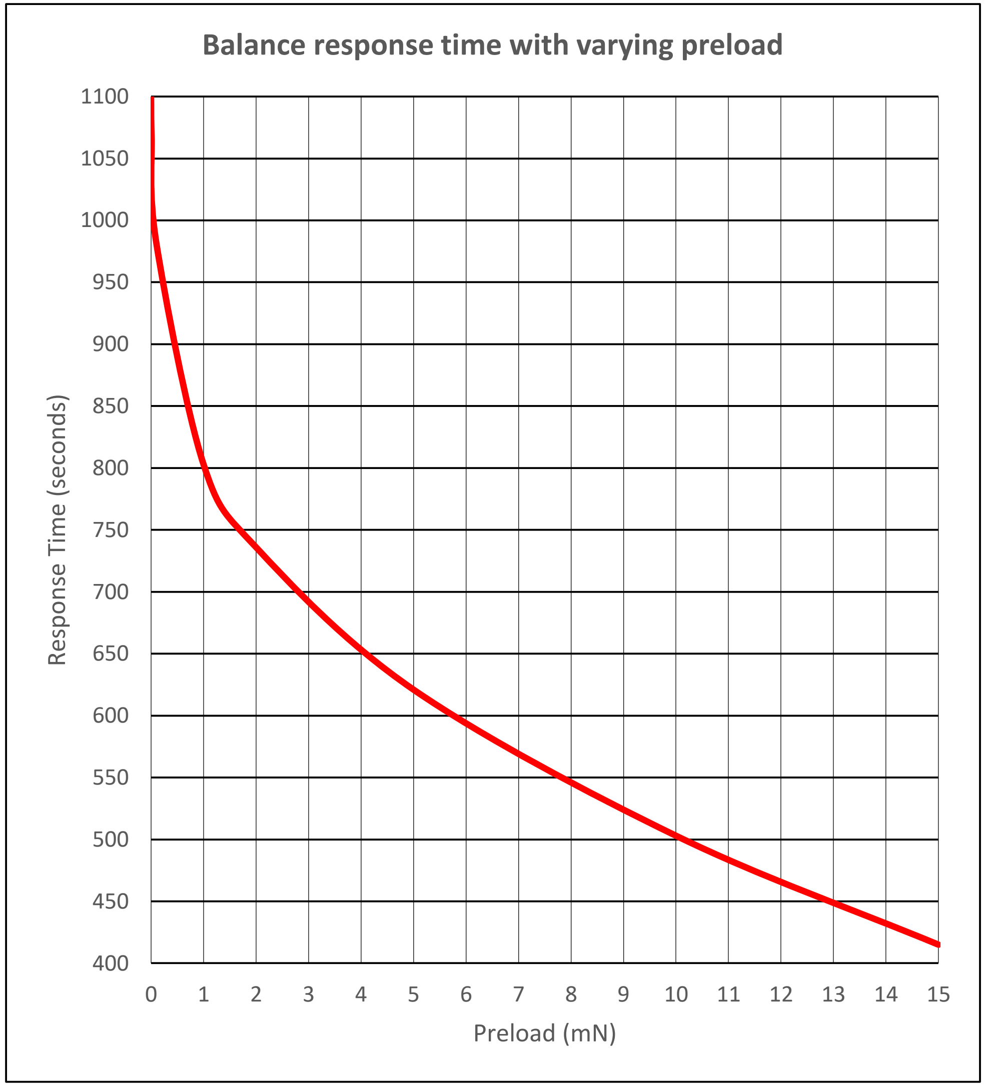
The response time to reach 300 degrees deflection for a static thrust of 30mN is plotted against pre-load.

Clearly for zero preload the response time tends to infinity.

Therefore no thrust can be measured in this condition, when all input energy is converted to kinetic energy, and stored energy tends to zero.

This is a simple demonstration of EmDrive obeying the law of Conservation of Energy.

This has implications for very high resolution balances where the the pre-load approaches zero.



Worldwide EmDrive Experimental Programmes (Jan 2018 Data)

COUNTRY	ORGANISATION	TECHNOLOGY	TECHNICAL STATUS	SOURCES	PROGRAMME TYPE	BASIS OF DESIGN
USA	USAF/NSA	1G Flight	Flight Qualified		Government	SPR Flight Thruster transferred to Boeing
		3G Theory	Theory agreed			SPR Patent & IAC13 paper
	NASA	1G Experimental	Thrust measured		Government	Scaled from SPR experimental thruster + dielectric
	NRL	1G Experimental	No data		Government	NASA thruster dimensions
	CANNAE	1G Experimental	Thrust measured		Commercial	Accelerator cavity plus dielectric input
		2G Experimental	Thrust measured			
	LA company	1G Experimental	Correct resonance achieved		Commercial	NASA thruster dimensions No dielectric
	Northrop Grumman	1G Experimental	No data		Commercial	Scaled from SPR Flight Thruster
China	NWPU	1G Experimental	Thrust measured		Academic	SPR Demonstrator Thruster
		1G Development	Flight Qualified			Scaled from SPR Flight Thruster
		3G Theory	Theory agreed			SPR patent & IAC13 paper
	CAST	1G Development	Flight qualified		Government	Chinese design
	Harbin Institute + Industry	1G Development	Flight Qualified		Commercial	Scaled from SPR Flight Thruster
Israel	Haifa company + Technical Institute	1G experimental	Thrust measured		Commercial	Based on SPR Flight Thruster
Germany	Dresden University	1G experimental	Thrust measured		Academic	Very low Q

Notes.

1.Russian EmDrive technical status unknown.

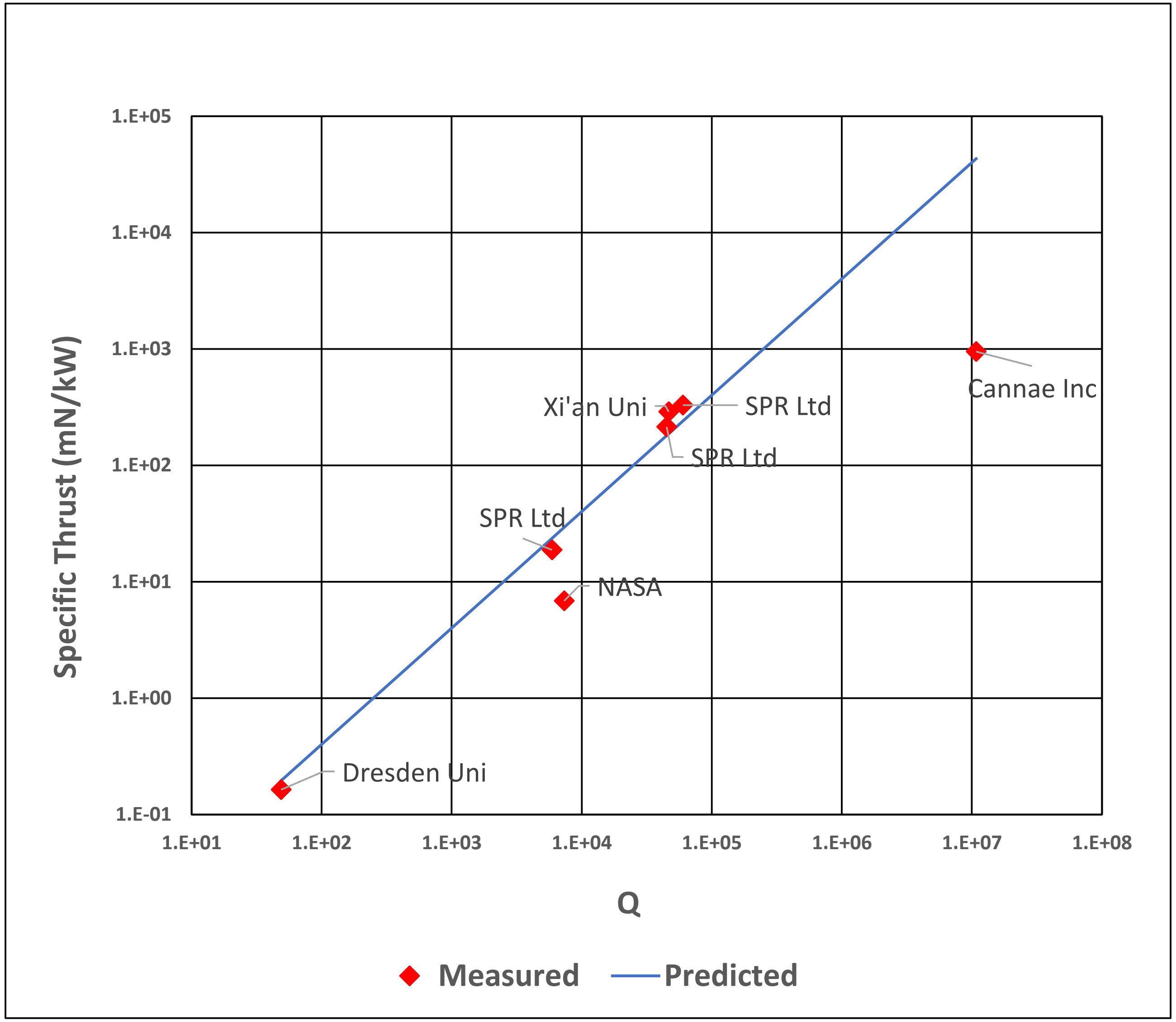
2.Individual Researchers experimenting in US, Germany, Australia, Canada, South Africa, Romania and Poland.

3.Theoretical studies in UK, US, France, Argentina, Brazil, Finland and Portugal.

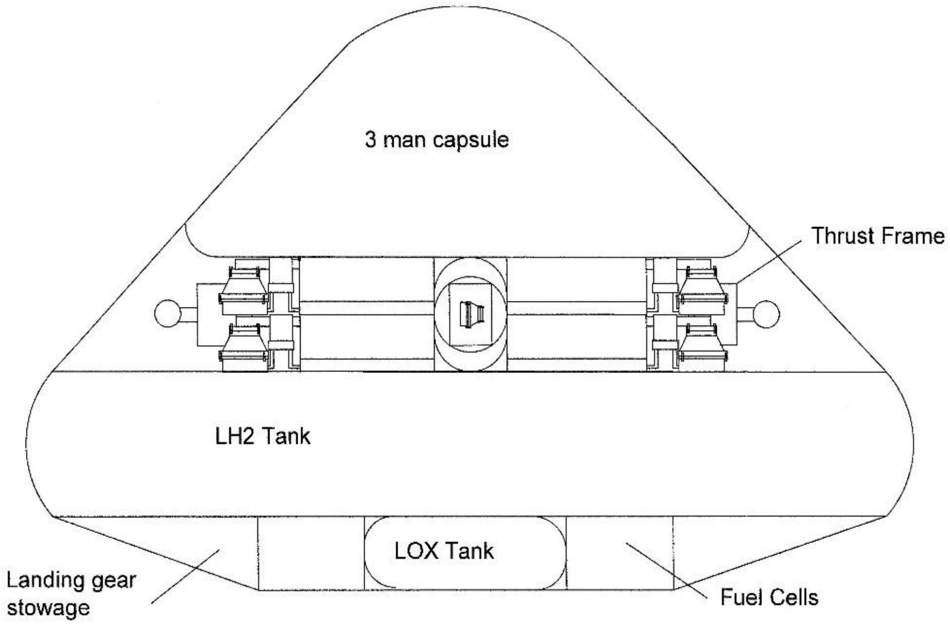
2015 Published EmDrive Test Data

Published specific thrust/Q
data for:
7 Thrusters
5 Research groups
4 Countries

Predicted specific thrust
for D_f =0.6



Manned Moon Mission using 3G Personal Space Vehicle (PSV)



Mission. Reusable Manned Moon landing and return

Payload. 4.5 Tonne manned capsule or unmanned cargo.

Total launch mass. 10,434 kg

Diameter 9m

Height 5.7m

LH2 volume 43,000 litres

LOX volume 560 litres

Max velocity 10,125 mph (200mph in atmosphere)

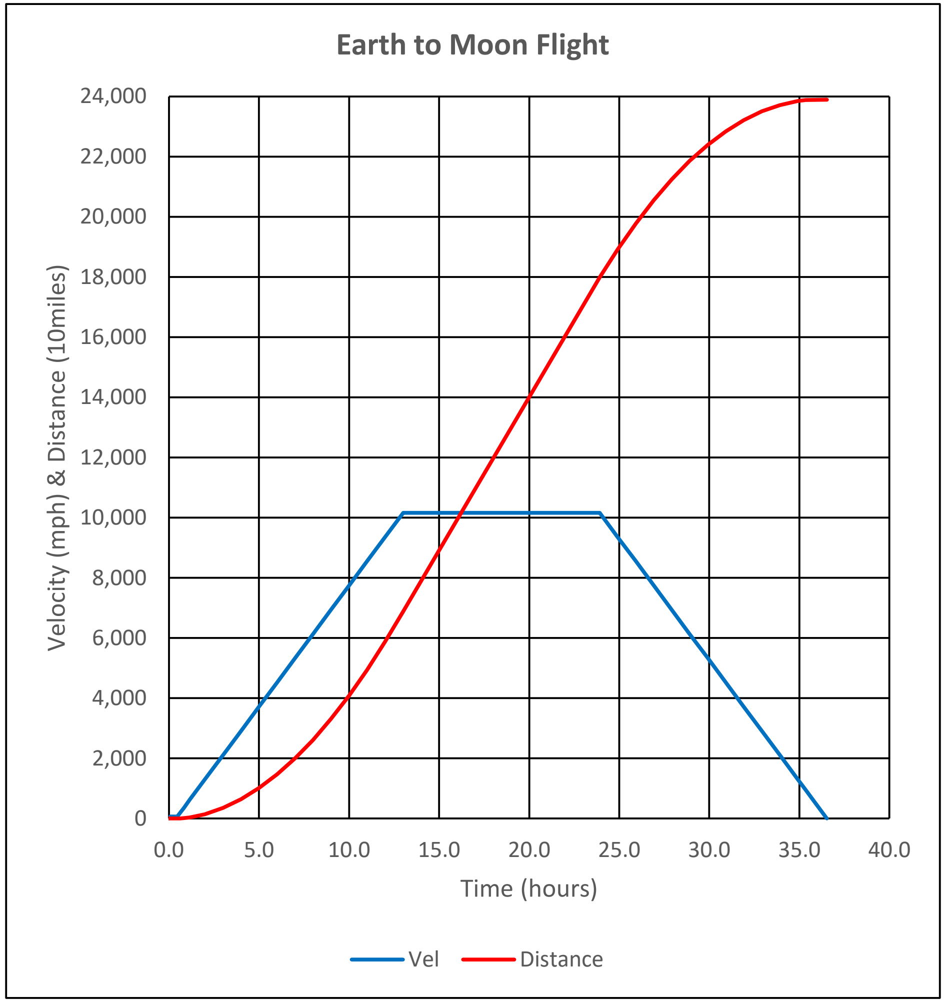
Max acceleration 0.01g

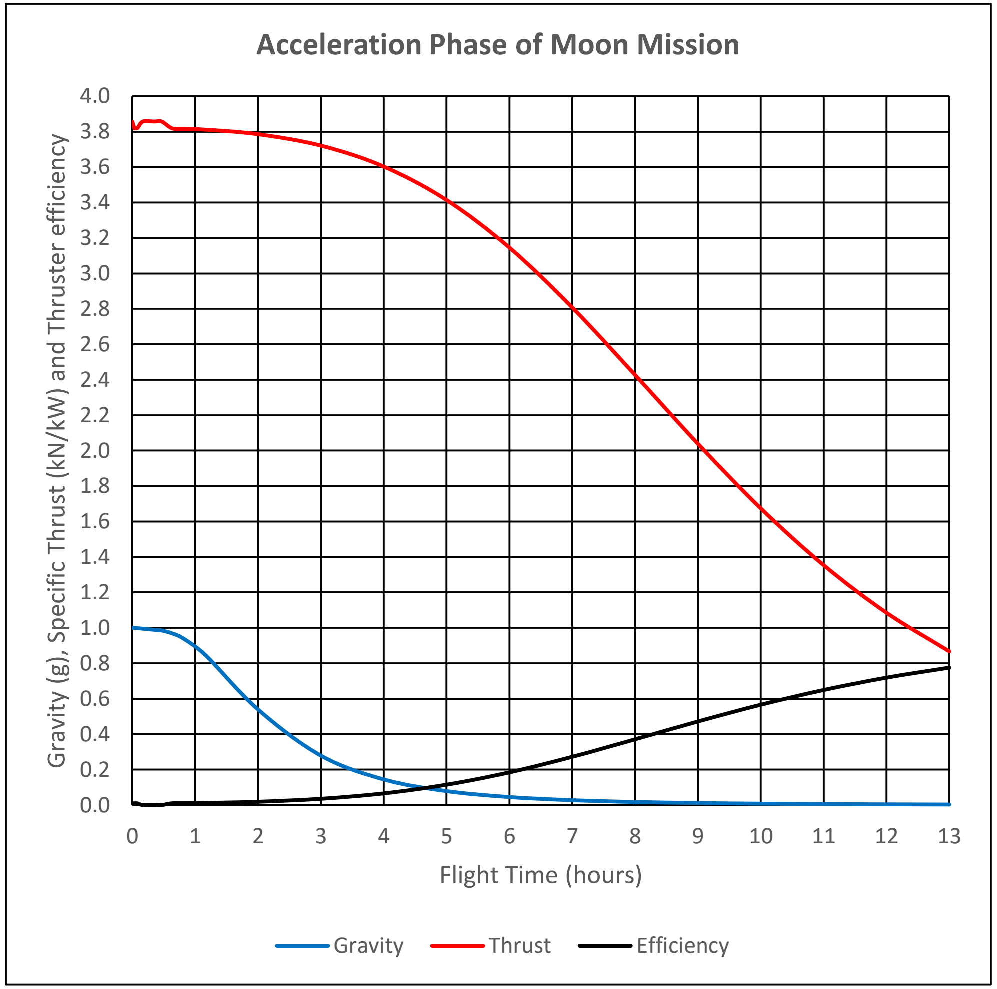
Total Flight Time for forward and return flights. 72 hours

Propulsion. 8x 4.25kW Fixed 3G Thrusters.

Attitude Control. 4x500W 2G Thrusters, single plane gimballed.

Moon Mission Analysis





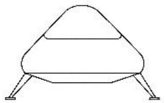
Technology Comparison to Scale

3G EmDrive will cause big problems for current space companies reliant on conventional propulsion technology

Low aerodynamic and thermal stress enable low-tech vehicle construction.

EmDrive propelled direct Earth to Moon flights are very efficient.

1960s Rocket	**2020s EmDrive**
Saturn V	PSV
3 men to the Moon and back	3 men to the Moon and back
110.6 m high	5.7 m high
2,970 Tonnes	10.4 Tonnes



EmDrive Multirole Spaceplane

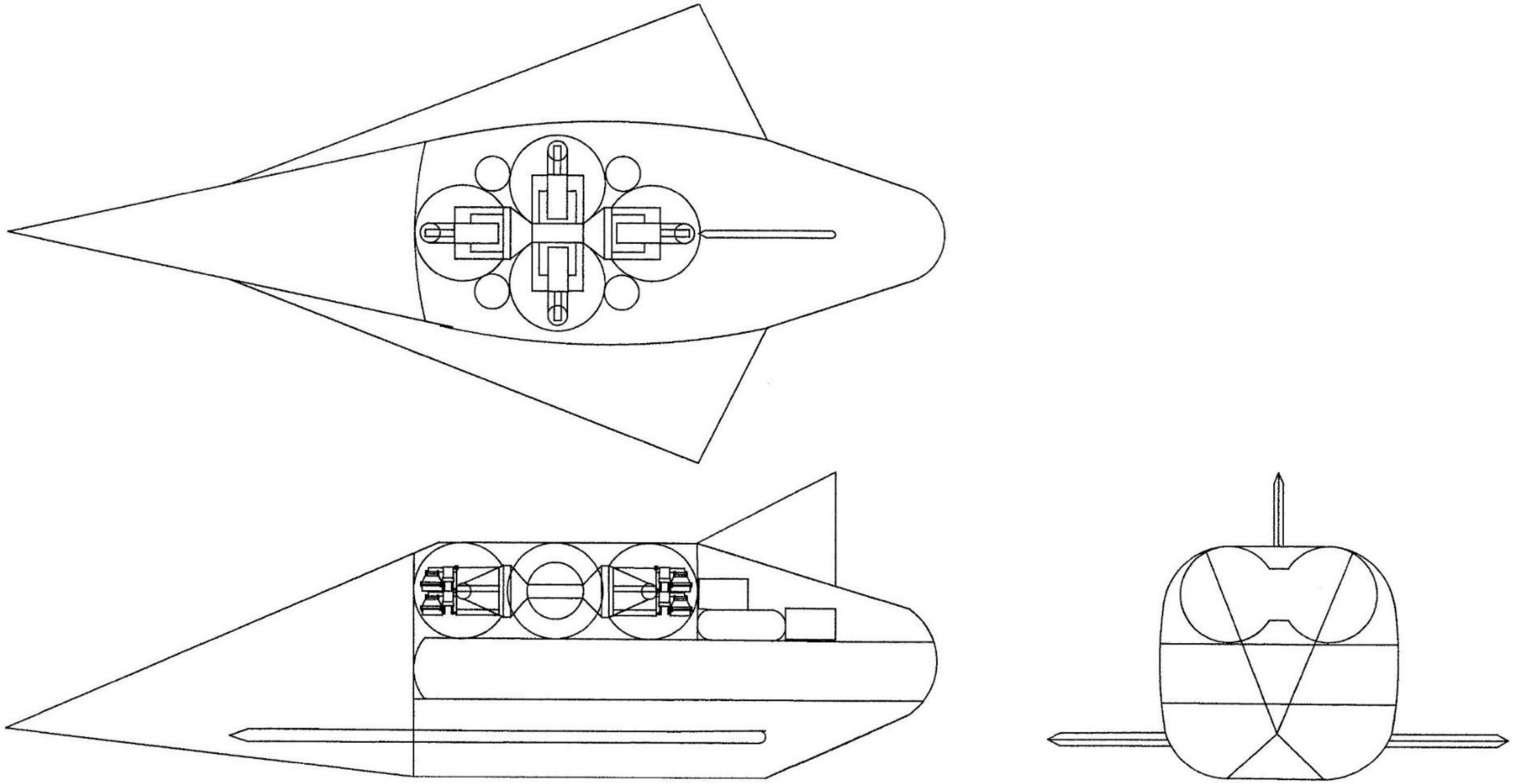
PSV thrusters gimballed in 2 axes

Sub-orbital/orbital/Moon landing

Manned/unmanned

Payloads: Satellites
Passengers
Cargo
Bombs

Operation: VTOL
Aero-braking and glide
Silent
Green



Conclusions

1.Design cavity using microwave industry standards. Avoid cut-off and close unwanted modes.

2.Do not expect "new physics" (or Magic!) to help you.

3. Maximise Q and Design Factor within achievable dimensions and tolerances.

4. Minimise wave-front phase error using shaped end plates and accurate alignment.

5. Design input circuit to match wave impedance.

6. Use cavity power detector probe to maximise power transfer to cavity and to measure loaded Q.

7. Test the thruster within the laws of conservation of momentum and conservation of energy.

8. Use thrust equation to verify measured thrust.

9. Use Design Factor to verify cavity temperature profile.

10. EmDrive technology is immensely disruptive and dual-use. Commercial and National programmes are secretive and academic programmes will be controversial.